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PREFACE

Among the various joining techniques, in the last years thermally controlled processes assumed an increasing significance in the manufacture of different types of hardware. However, the penetration of welding as the dominating joining technology in aerospace industry is rather slow. An encouraging tendency for applying welding processes in the production of aircraft structures can presently be observed, but parallelly a decreasing tendency may be noticed in airframe construction, where riveting still is the prevailing production method.

Reasons for this deviation from the general trend of exploiting welding in production technology may be partly attributed to the numerous problems existing in welding high strength, low density aerospace materials. However, it also seems that inadequate knowledge of the advanced joining techniques and of the properties of joints by the design engineers plays an essential role.

In order to exploit welding and associate methods – such as brazing, thermal cutting, thermal spraying, metal bonding etc. – in production, many Welding Associations in various countries have assumed a leading part for many years. Particularly caused by the International Institute of Welding, an increasing attention now is being paid on national and international coordination of research and development. In the field of aerospace industries, the German Association for Welding Technology (DVS), the Welding Institute in the United Kingdom, the American Welding Society, the Institut de Soudure in France, and the Welding Societies of all other NATO countries make every effort to improve their cooperation in this field.

Some fruits of such a cooperation are the increasing tendency for common standardization, technical discussions on the problems connected with welding, and other useful kinds of communication.

According to these intentions, it is the aim of this Lecture Series to give support to a better knowledge and better understanding as well as to an improved exploitation of advanced welding technology in the aerospace industries.

HANS-DIETER STEFFENS
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INTRODUCTION

by

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All high strength materials are more or less sensitive to a change in structure caused by welding or other heat - intensive processes. Increasing attention is now being paid to measurements of the mechanical behaviour of the weld seam, especially of the heat - affected zones. In accordance with the chemical composition as well as the heat treatment of the various alloyed materials, their weldability is quite different, and thus different joining methods are required.

There is no doubt that the development in welding is following two lines; one being the improvement of the materials' weldability in order to avoid hot and cold cracking, stress corrosion sensitivity etc., the other dealing with the development of the joining processes in order to improve their economy or to minimize detrimental influences on the parent metals, such as residual stresses and distortion, heat-affection and geometric discontinuities.

As far as welding processes are concerned, no method exists, the application of which would guarantee the absence of weld defects. Thus, costly premature failures in important engineering structures could occur in the past, initiating an increasing concern with weld imperfections. In order to avoid weakness or failure by defects on the one hand, an unjustified rejection of properly joined structures on the other, numerous destructive and nondestructive investigations have been carried out. As a result, weld design practices were improved and meaningful weld acceptance criteria could be established. Still the work is going on involving all those concerned with welded structures, as neither the designer nor the metallurgist, welding engineer, fabricator, inspector, quality assurance specialist or the final customer can feel unconcerned in welded structure integrity.

This is the reason why nowadays a discussion of advanced joining techniques inevitably includes advances in fracture mechanics and fatigue as well as progress in nondestructive testing procedures. In view of these facts it was evident that renewed attention had to be focused on the role of destructive and nondestructive test methods.

Also, some non-welding joining processes as high-temperature brazing and metal bonding by plastic adhesives had to be considered due to the growing interest these joining methods find in aerospace manufacturing techniques. In order to meet the requirements for joining processes for high-strength materials, an increasing emphasis is continually being given to the development and application of high-temperature brazing techniques. Improved mechanical properties and the use of small scale brazed joints means that materials - even if not weldable - can be applied with a high degree of safety under conditions of high mechanical and thermal stress.

As far as metal bonding is concerned, the application limited to low temperatures; usually less than 200 °C. Recent advances in the development of adhesives permit metal bonded joints to be applied up to 400 °C with acceptable long term behaviour, and even up to 1000 °C for a short time. However, the price of these types of adhesives makes the procedure too costly for application even in aerospace industries. On the other hand, the low temperature adhesives offer numerous advantages especially in airfrance construction, where high percentages of cell structures and installation are bonded by plastic adhesives.

Conventional welding processes have already gained a considerably high level of perfection, and there are indications that their development is presently tending to more mechanization and automatization than to drastic changes of the fundamental procedures. Generally it is desired to replace welding skill of human operators by automatic functions in the welding equipment.

Such is the situation with TIG-welding where the skill involved in feeding the filler wire into the weld pool quite often has been replaced by an automatic wire feed unit. In MIG-welding, the mechanized equipment already represents the technical standard. However, due to its welding characteristics, it is hardly applied in aerospace industries. In TIG- as well as MIG-welding, the process development seems to be accomplished by introducing the pulsed arc.

In aircraft industries, many aluminium airframe construction parts are joined by the TIG and resistance weld processes, with both of them being applied to sheet thicknesses of 0.6 to 2.4 mm, and with higher thicknesses up to about 6 mm being restricted to TIG-welding.

Beside plasma arc and inertia welding, the electron-beam welding process is widely used in the aerospace industries. By means of this process, many components may be joined with excellent results which in the past could not be welded or only under difficulties.

Whereas EB-welding is hardly applied to aluminium in aircraft construction, it is going to become the most advanced welding process for complicated steel, titanium alloy or nickel-base superalloy components. Thus it is only a recognition of the meaning of this process that it is preferentially discussed whenever advanced joining techniques are mentioned. Indeed it offers a deep penetration with a high depth-to-width ratio and small heat-affected zone which generally is not achieved by other fusion weld processes.

Though also in this process - as in any other welding process - defects can occur, EB-welding will continually gain new applications as for example in large structures built up from smaller segments. In the case of EB-welding, a considerably rapid development can be observed including, for instance, electronic control systems for precise seam tracking, programmed beam deflection, high-, low- and non-vacuum welding, and machines employing local vacuum.

In contrast to the high standard of EB-welding devices, the state of development of deep-penetrating high power lasers is still at the beginning. Though to date welds in a variety of metals and alloys have already been produced by convectively-cooled, coaxial CO_2 lasers, cross-beam lasers and other gas-transport or gas-dynamic lasers. With some exceptions, no significant applications have matured in aerospace industries. The desire to achieve beam outputs of 10, 20, 50 kW or more could not meet the requirement for compact, flexible welding tools. During the last five to six years, however, it was shown theoretically and experimentally that the physical limits preventing rapid development of "conventional" gas-dynamic CO_2 lasers could be crossed by the conception of the gas-dynamic "mixing" laser (GDML). In this device, nitrogen is heated up in an arc chamber to temperatures between 2000 and 3000 K, and is then expanding through a nozzle system, with CO_2 and water or helium being added in the area of supersonic flow. This rather simple principle enables power outputs of 20 to 36 kW for current designs, and from a theoretical viewpoint alloys unlimited power usage for future designs. However, difficulties exist in connection with the mixing of gas streams at their extremely different temperatures and with the filtering and recycling of the nitrogen in these devices.

In spite of all disadvantages, there is a growing interest in the potential applicability of high power lasers to industrial welding tasks, and it seems worth while to carefully watch the developments in this new branch of welding procedures.

Attention should be paid, also, to the continued development of solid state diffusion bonding. This process is able to join detail parts into integral configurations with a continuous metallurgical structure by applying pressure and heat for a predetermined period of time in an adequate environment. The potential of diffusion bonding has already been recognized in manufacturing helicopter rotor hubs and jet engine components.

A strong effort is also observed in thermal spraying procedures and their application in engine components. Especially recent developments in both equipment and processes in plasma arc spraying of metallic and non-metallic powder materials offer the potential of even greater industrial usage. The most remarkable application is the surface protection of turbine rotor blades which - in the past - has always been one of the unsolved problems in improving the efficiency and life endurance of jet engines.

This process will be discussed in the lecture series as well as the present status and future development of thermal cutting procedures.

It is the aim of the authors to provide a comprehensive survey of the joining processes and their application in aerospace industries, thus contributing to an exploitation of welding and similar processes in production technology.

ADVANCED JOINING TECHNIQUES IN AEROSPACE CELL STRUCTURES

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SUMMARY

This paper is concerned with the selection and use of joining processes for various types of airframe applications. General aspects of advantages and difficulties in welding critical primary aircraft structures are discussed. The all-welded F-14A Wing Center-Section is used as an example to delineate the types of problems inherent in selecting the optimum welding process and procedures to assure structural integrity, minimum cost, distortion control and light weight.

The aerospace industry is particularly interested in joining titanium, steel and aluminum alloys in various gages ranging from thin sheet to heavy plate, 2 to 3 in. (50 to 75 mm) thick. Various welding processes and applications are discussed in relation to selection criteria. Developments in electron-beam welding small and large titanium structures are presented with particular attention given to high vacuum welding and directions being taken in non-vacuum and sliding-seal electron-beam welding. Applications of pulsed gas-tungsten-arc, plasma-arc (welding and cutting), laser beam (welding and cutting), weld-bonding, diffusion bonding, and brazing are discussed.

The paper continues with a discussion of design for use of modern methods of weld inspection, the effects of defects on weld performance and some experiences in testing large structures. Recommendations for use of design and test data evaluations to minimize cost, increase ease of fabrication, facilitate inspection and increase reliability confidence conclude the paper. A summary is presented of the niches the various processes are filling and the potential for future advances in facilitating economical, reliable fabrication of airframes.

INTRODUCTION

In the last decade, stringent demands for higher performance supersonic aerospace vehicles have caused industry to make significant advances in material and process usage for the design and fabrication of critical aerospace structures. As a result designers were faced with the problem of producing major structures which required emphasis on improved materials utilization to minimize weight and cost. In the case of metallic structures, monolithic structural components were designed which reduced the need for mechanical fasteners and increased the need for reliable welding brazing and solid-state joining processes.

In many designs, welding has replaced mechanical fastening to eliminate the fastener itself and the increased material required in the part due to the hole penalty. Because of its notch (K_t) factor, the penalty can be as high as $2\frac{1}{2}$ times the weight without a hole. When fasteners are used to join components, loads passing through the structure concentrate at points in the structure which cause such a material penalty. The anticipated wear and fatigue at these points must be compensated for by increasing the size and number of fasteners employed, resulting in increased assembly cost and weight.

Therefore, in many developmental and production aircraft programs, such as the B-70 supersonic transport (SST), F-111, F-14, Cheyenne helicopter, multi-role combat aircraft (MRCA) and B-1 bomber, welded structures became a reality. In addition to fusion welding, solid-state joining and specialized combinations of processes (e.g., weld-bonding, weld-brazing) have been investigated for potential applications. Table I summarizes a number of major applications in which welding processes have been applied or considered as primary contenders for production.

Table 1 Major Airframe Applications of Weldments by Various Welding Processes

WELDING PROCESS/APPLICATIONS
EB
• CLOSE-OUT WELD ON THE WING TO STUB-WING-FUSELAGE ATTACHMENT IN THE B-70 PROGRAM
• ROTOR HUB FROM 2.250-IN.-THICK Ti-6Al-4V FOR THE CHEYENNE HELICOPTER
• F-14A CENTER WING BOX STRUCTURE (ANNEALED Ti-6Al-4V)
• F-14A UPPER AND LOWER WING COVERS (ANNEALED Ti-6Al-4V AND ANNEALED Ti-6Al-6V-2Sn)
PA
• INTEGRALLY STIFFENED WING PANELS (Ti-6Al-4V) APPROXIMATELY 28 FT LONG ON SST PROGRAM (0.125-IN. THICK)
• MANUAL REPAIR WELDING ON F-14A
GTA
• ORBITAL ARC TUBE WELDING (Ti-3Al-2 1/2V) ON F-14A
• F-111A WING CARRY-THROUGH STRUCTURE OF D6AC STEEL (UPPER COVER BOLTED ON), MULTIPASS WELDING REQUIRING PRE-HEAT
• VARIOUS STRUCTURAL PARTS ON B-1 AIRCRAFT, INITIAL STRUCTURES

Currently, the F-14A, MRCA and B-1 aircraft are primary examples which utilize welding techniques for fabrication of airframe structures. Each of these aircraft employs fusion welding for fabrication of its center wing-box. The F-14A employs an all-welded, center wing box (Fig. 1) that is fabricated from 35 parts with 70 full-penetration electron-beam (EB) welds. The wing box weighs 2065 lb and is 19 lb lighter than its original target weight. Furthermore it is the least expensive structure ($/lb) in the F-14A airframe. It has also been determined that bolting on the upper and lower covers would eliminate 33 welds but, in turn, would increase the estimated overall weight of the box by 20%.

Critical characteristics which must be considered in employing welding on an airframe are:

- Mechanical property stability over the design temperature range for the airframe lifetime
- Fatigue and fracture propagation characteristics of weld joints.

The following sections discuss materials and weld process selection criteria. This is followed by discussion of specific process applications including non-destructive inspection and defect significance.

MATERIALS SELECTION

Early aircraft were designed to static strength criteria. As the designer learned to reduce weight while still meeting static strength requirements, flutter problems in the structure became significant. Ultimately these problems were resolved. Fatigue problems were later encountered. Since then, static strength, aeroelasticity and fatigue life have been the three main criteria used in design of aircraft. Static strength (easiest to evaluate) is usually the starting point and sizes the structure. Then aeroelasticity calculations are determined relative to meeting flutter requirements. Fatigue calculations come later in the design, but stress concentrations are always considered during the design phase.

An example of why static strength cannot be the sole design consideration in aluminum alloys is 7178 aluminum. Even though 7178-T6 aluminum appeared to be superior in strength to 2024T-4 and 7075-T6, it did not have the required toughness and fatigue properties. This alloy is now banned in aircraft. At the time that the 7178 alloy was first used, though, the fracture mechanics understanding that we have today was not available and, therefore, could not be used.

The basic equation of fracture mechanics relates the critical crack size, $\underline{a}$, to the operating tension stress, $\underline{s}$, a geometric (dimensionless) factor, $\underline{\lambda}$, and the plain strain fracture toughness, K_{IC} as indicated:

$$a = \lambda \left(\frac{K_{IC}}{s}\right)^2$$

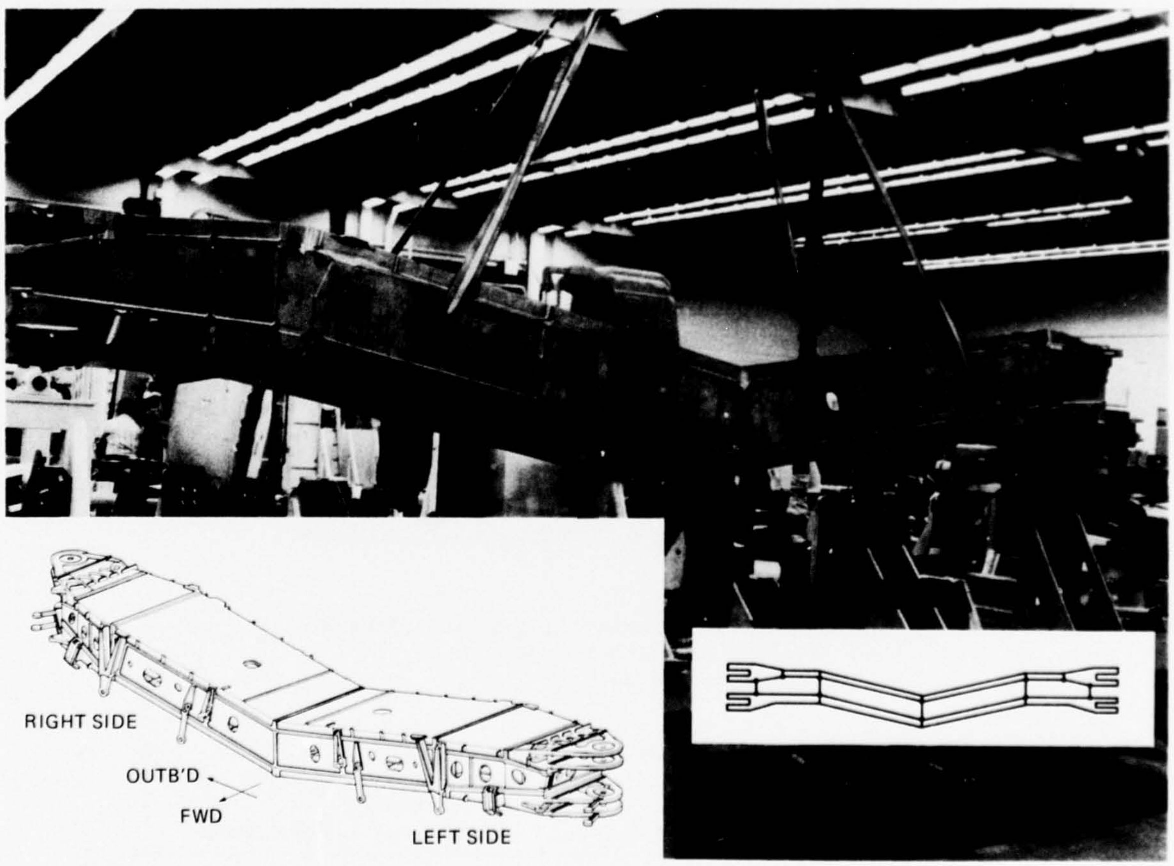


Fig. 1 F-14 Wing Center Section

At the calculated value of a for a given material, *rapid (catastrophic) crack growth is supposed to occur.* K_{IC} is considered to be a basic material parameter. When one looks at the fracture toughness and critical crack size, it is indicated that some alloys should be able to safely sustain cracks as much as ten times larger than others. It is also easier to find such cracks by NDI.

The more recent aircraft, therefore, have design specifications that assume that an undiscovered flaw of a prescribed size exists in the most critical part of the structure. The airframe producer today must demonstrate that this undiscovered flaw will not grow to critical size in two to four lifetimes. Flaw growth tests of pre-cracked specimens and spectrum tests have been used to assure that various designs including weldments can meet rate-of-crack-growth (da/dn) requirements as well as fracture toughness (K_{IC}).

One of the major objectives of later designs which is still continuing is to use materials which are moving upward and to the left in the toughness vs. yield strength curves for aluminum, titanium and steel as depicted in Fig. 2. This effectively is intended to result in an increase in the critical crack length for a given design stress, thereby increasing the possibility of discovering cracks in service before failure and also possibly providing some increased life.

As indicated in Table I on major applications of weldments, the F-111A wing carry-through structure was the first major weldment flying using D6AC steel and GTA welding with preheat of at least 350°F. Early studies at Grumman on fracture toughness indicated, however, that based on figure-of-merit annealed Ti-6Al-4V titanium alloy would be a good selection for fracture-critical parts and it was selected for the all-EB-welded, F-14A wing center-section. *Both the B-1 and MRCA also selected the* Ti-6Al-4V alloy for their center wing boxes. It is, therefore, convenient to base further discussion of advanced joining techniques primarily on titanium alloys.

It has been the practice to use annealed alpha-beta type titanium alloys (e.g., Ti-6Al-4V and Ti-6Al-6V-2Sn) because of their fabricability and to insure sufficient fracture toughness and tensile ductility in the weld and heat-affected zone (HAZ). While use of annealed alloys permits control of fatigue and crack propagation, maximum weight reductions are not attainable. Therefore, programs are now in progress to develop weldable alloys that have good fatigue and crack propagation characteristics at higher yield strength levels than the annealed alpha-beta alloys. Table II shows typical room-temperature tensile and fracture toughness properties of selected alpha-beta and beta alloys with their respective densities. To obtain adequate fracture toughness and increased yield strength, it is necessary to employ solution-treated-and-aged (STA) material which preferably would be welded and machined in the solution-treated (ST) condition and aged after welding. Base-metal properties indicate that the beta alloys having yield strengths above 160 ksi give better fracture toughness values than alpha-beta alloys at yield strengths of 120 to 140 ksi (min) and, therefore, were considered as candidates for future use on a recently completed Air Force program (Ref. 1). The weldability results obtained are discussed in greater detail in a subsequent section.

Steel alloys offer a possible alternative that could have the required properties at low cost. Some work on HY-180 and higher alloy steel is progressing at the present time, but has not been successful in replacing titanium alloys. Even if a steel substitute is found, it is very possible that a new titanium alloy will be discovered that will have the beta-titanium alloy toughness with improved fatigue at high yield strength levels. Regardless of the outcome of such studies, the necessity for welded structures will not decline for economically produced high-performance aircraft.

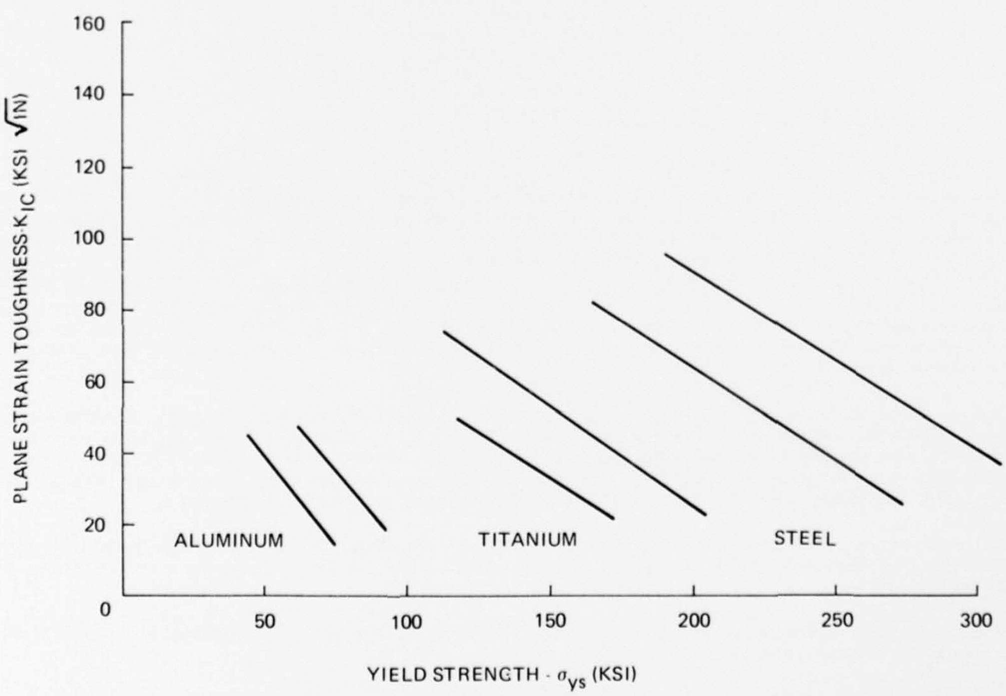


Fig. 2 Trends in Toughness Variation

Table II Typical Room-Temperature Properties of Titanium Alloys

TITANIUM ALLOY	DENSITY, LB/CU IN.	ANNEALED		STA	
		F_{tu}/F_{ty}, KSI	K_{IC}, KSI $\sqrt{IN.}$	F_{tu}/F_{ty}, KSI	K_{IC}, KSI $\sqrt{IN.}$
Ti-6Al-4V	0.160	130/120	50-60	160/145	36
Ti-6Al-6V-2Sn	0.164	150/140	35	170/160	27
Beta III	0.184	115/100	—	175/165	65
Beta C	0.174	120/113	—	173/167	58
Ti-8Mo-8V-2Fe-3Al	0.174	126/125	—	175/165	54
Ti-6Al-2Sn-4Zr-2Mo	0.164	130/120	—	145/130	32
Ti-6Al-2Sn-4Zr-6Mo	0.169	160/162	—	175/165	25
Ti-6Al-6Sn-4Zr-4Mo	0.168	—	—	175/165	45

WELDING PROCESS SELECTION

In the selection of joining processes for specific applications, criteria that must be considered are part criticality, weld properties, equipment capability, availability, cost, repeatability, joint design, inspectability, equipment stability, repair and salvage. All of these considerations must be evaluated relative to the specific requirements and judgments made by the fabricator to satisfy the most reliable and cost-effective needs. This can be seen in the process selections that have been made in the past as noted in Table I for various vehicles and the circumstances that prevailed at the time the processes were selected. This will become apparent in subsequent sections which discuss various joining applications that have been proposed or are in use primarily in the United States.

In the following sections, we will consider electron-beam, plasma-arc, laser and gas-tungsten-arc welding processes, diffusion bonding, weld-bonding, and brazing relative to actual or proposed applications. Qualitative evaluations of welding processes based on useability and cost factors are presented in Tables III and IV. These will serve only as guidelines and generally apply mainly to titanium alloy welds greater than 1/4 in. thick. Other processes used essentially on thin-gage structures are evaluated in the pertinent discussions that follow.

ELECTRON-BEAM WELDING (HARD VACUUM)

Generally, there are three types of EB welding, classified according to vacuum level attained at the weld:

- Hard Vacuum (high vacuum) at 10^{-4} to 10^{-5} torr
- Soft Vacuum (medium vacuum) at 10 to 100 torr
- Out-of-Chamber (non-vacuum) at 760 torr.

The above vacuum levels do not apply to the levels attained at the filament of the gun except for the case of hard-vacuum welding. This level is the minimum required to prevent rapid degradation of the filaments. Table V shows the effect of pressure level on the purity of atmosphere and the relative frequency of gas molecules collisions. In a hard vacuum (10^{-4} to 10^{-5} torr), the electron-beam is not affected much by gas molecules and can be focused over a distance of two feet or greater depending on gun design. The frequency of collisions being directly related to the concentration of gas molecules in the chamber is still not significantly increased to reduce weld penetration noticeably at 10 to 100 torr. Above 100 torr, however, penetration rapidly deteriorates until at 760 torr gun-to-work distances are reduced to less than one-half inch to penetrate sheet-metal steels. This is very similar to most arc-welding process arc length requirements. It is also generally necessary to employ high voltages of 100 to 175 kv to weld at atmospheric pressure.

The excellent purity levels of the hard vacuum assure that interstitial pickup of oxygen, nitrogen and hydrogen in the weld is virtually eliminated. Hydrogen has been generally blamed for most of the problems experienced with titanium weldments in the past and only high hydrogen in the base material or that resulting from improper joint preparation can cause problems. Although purity of atmosphere has been generally cited as the main advantage for using vacuum EB welding, other advantages of vacuum welding have been ignored in the past.

The comparison of the EB center wing box structure application with the GTA steel carry-through structural application demonstrates readily the advantages of electron-beam welding for primary aircraft structure. The advantages include:

- High depth-to-width ratios and narrow weld beads produced in 2-in.-thick material in a single welding pass (no filler wire necessary)
- Small grains in welds with narrow heat-affected zones resulting in improved static and dynamic mechanical properties (joint efficiencies approaching 100% base metal)
- Extremely pure welding atmosphere in vacuum chamber virtually eliminates weld contamination

Table III Comparison of Welding Processes Based on Usability Characteristics

USABILITY CHARACTERISTIC	EB WELDING	PA WELDING	GTA WELDING	GMA WELDING
COMMON THICKNESS RANGE, IN.	FOIL TO 3	1/8 TO 3/8	1/32 TO 1/4	1/4 TO 3+
EASE OF APPLICA-TION	FAIR TO GOOD	GOOD	GOOD	FAIR
EASE OF WELDING	EXCELLENT	GOOD	GOOD	DIFFICULT
GROOVED JOINT REQUIRED	NO	NO	OFTEN	ALWAYS
AUTOMATIC OR MANUAL	AUTOMATIC	BOTH	BOTH	AUTOMATIC
MECHANICAL PROPERTIES	EXCELLENT	GOOD	FAIR	FAIR
QUALITY OF JOINT	EXCELLENT	EXCELLENT	GOOD	GOOD-FAIR

Table IV Comparison of Welding Processes Based on Cost Factors

COST FACTOR	EB WELDING	PA WELDING	GTA WELDING	GMA WELDING
EQUIPMENT	VERY HIGH	MODERATE	LOW	HIGH
WELDING (LESS EQUIPMENT)	LOW	LOW	HIGH	MODERATE
WIRE REQUIRED	NO	SOMETIMES	OFTEN	ALWAYS
V GROOVE REQUIRED	NO	NO	OFTEN	ALWAYS
DISTORTION	VERY LOW	MODERATE	VERY HIGH	HIGH

Table V - Effect of Pressure Level on Purity of Atmosphere and Relative Frequency of Gas Molecule Collisions

PRESSURE, TORR	GASES, PPM	NUMBER OF MOLECULES*	REL FREQUENCY OF COLLISIONS
10^{-5}	0.01	5,800	1
10^{-3}	1.3	580,000	100
10^{-1}	132	58,000,000	10,000
4×10^{-1}	500	– –	– –
760	– –	4.4×10^{11}	100,000,000

*IN A CUBE 0.001 IN.(0.0254mm) ON A SIDE
(A VOLUME OF 10^{-6} CU IN. OR 16.4×10^{-6} CU MM)

- High welding speeds of 15 to 60 in./min normally used for thicknesses 1/2 in. or greater resulting in excellent shrinkage and distortion control
- Mechanized welding operation resulting in repeatable electron-beam weld certifications
- Minimized machining of weld joints (straight butt welds, no grooves employed)
- All thicknesses weldable with the same EB gun
- Generally, even high-strength steels can be EB welded without preheating.

For the last eight years, Grumman has been using EB welding as a production method on the F-14A Naval Air Superiority Fighter Aircraft. Figures 1 and 3 show the wing center box and its location in the aircraft. Over 300 of these structures have been produced and accepted by quality assurance for actual use. This structure uses Ti-6Al-4V titanium alloy in the annealed condition which has resulted in improved material utilization when coupled with EB welding to minimize weight and cost.

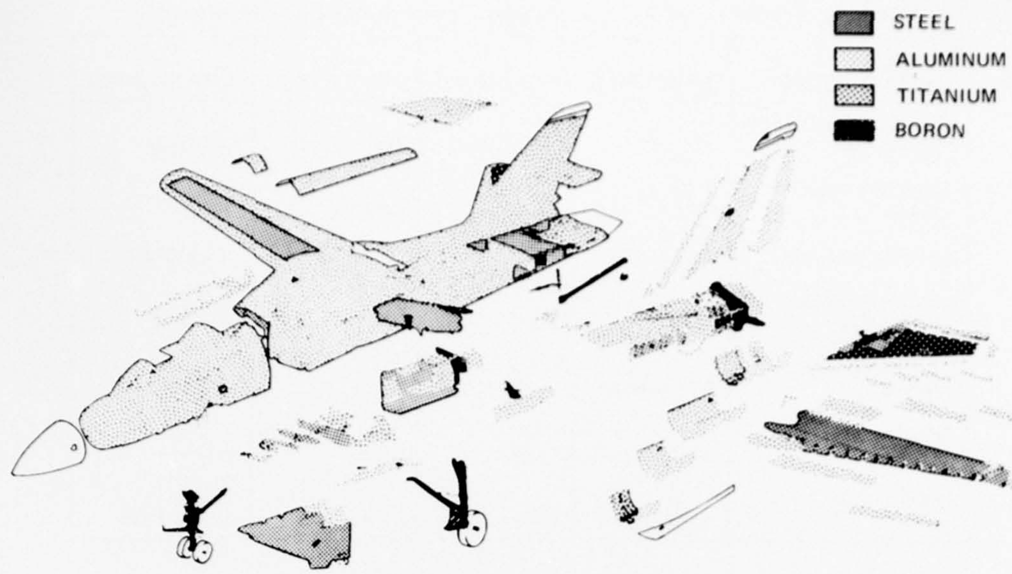


Fig. 3 F-14 Structural Components

Figure 4 shows the layout of the self-contained production facility which includes controlled areas for welding, quality assurance, machining, heat treating, chemical cleaning and forming operations. The welding facility (Figure 5) is located in an enclosed, positive-pressure, clean area (80,250 ft^2) in the southeast corner of a major production plant. Table VI shows the EB welding chamber capacities. Included in this area is a small development EB welder, offices for production support personnel directly related to the EB welding operation, a large production welding zone containing the four tunnel welders and one clamshell EB welder, plus additional space for loading and unloading each welder, and another large area where details and assemblies are stored and loaded into fixtures for cleaning and pre-fitting prior to welding. Seven electron-beam welders are located in or near the welding area (development, clamshell, tunnel (4), and sliding-seal). Previous work on the sliding-seal is presented in a subsequent section.

The EB gun essentially consists of an electrode, an anode and a focusing coil. Magnetic focusing, oscillation and deflection are provided. Welding parameters relating to the gun are:

- Voltage and Current - directly affects penetration in proportion to the variation
- Focus - inversely affects penetration in proportion to the power density variation
- Welding Speed - distributes power over a given distance in a given time and generally inversely affects penetration.

Automatic monitoring of the operation is aided by a digital position readout system which displays the position of the gun relative to the part. Measurement errors with the device are noncumulative. In addition, a scanner is available to display an image of the weld joint on an oscilloscope prior to welding. It shows the relationship between the beam and the weld joint center-line. A closed-circuit TV system with the camera in the EB gun uses a 45-deg mirror to show the geometrical beam location.

Experience with F-14A EB welding includes design, fabrication and successful static and flight-testing of an all-welded center wing box, and outer wing covers EB welded to the required pivot fittings. All of the material is annealed Ti-6Al-4V titanium alloy plate and forgings, except for the upper wing cover/pivot assembly which is annealed Ti-6Al-6V-2Sn titanium alloy.

As a result of the successful fabrication and test evaluation of an experimental electron-beam-welded torque box, a full-scale box was designed for the F-14A. Figure 6 shows the weld land configuration that was used to weld the 70 straight butt welds (89 in number when the first boxes were fabricated). Extensive test work showed that by using scribed witness lines on the top and root-side of each joint, missed joints and other defects could be readily identified, even prior to radiographic examination. Other efforts were directed toward parametric studies on various gages to establish optimum weld bead shapes and widths. A relatively parallel-sided weld of uniform width was developed. Minimum weld widths of 0.070 to 0.080 in. were made to assure that internal missed seams were not encountered in production welding. The witness lines on the top and root side of the weld help to locate the position of the weld bead relative to the original joint. It is required that at least 0.015 in. of weld be measurable on each side of the joint for acceptance.

The results of fatigue and fracture toughness tests were established to finalize the design of the box. Reweld studies were accomplished to determine the effect of rewelding on mechanical properties as well. It was found that multiple rewelds were not detrimental; as a result, various defects can be EB repaired. Investigation showed that fatigue properties were reduced by leaving the weld reinforcement intact or by eliminating stress relief after welding. Essentially 100 percent fatigue efficiency is obtained when reinforcement is removed and a stress relief at 1200°F for 4 hr is utilized after welding (Fig. 7). Lower stress relief temperatures reduce efficiency. Fracture toughness requirements call for K_{IC} of 70.0 for base metal and a minimum of 37.5 for EB-welded plate. Fatigue flaw growth tests were also run to establish critical flaw sizes for twice the spectrum fatigue life of the aircraft (Fig. 8 and 9).

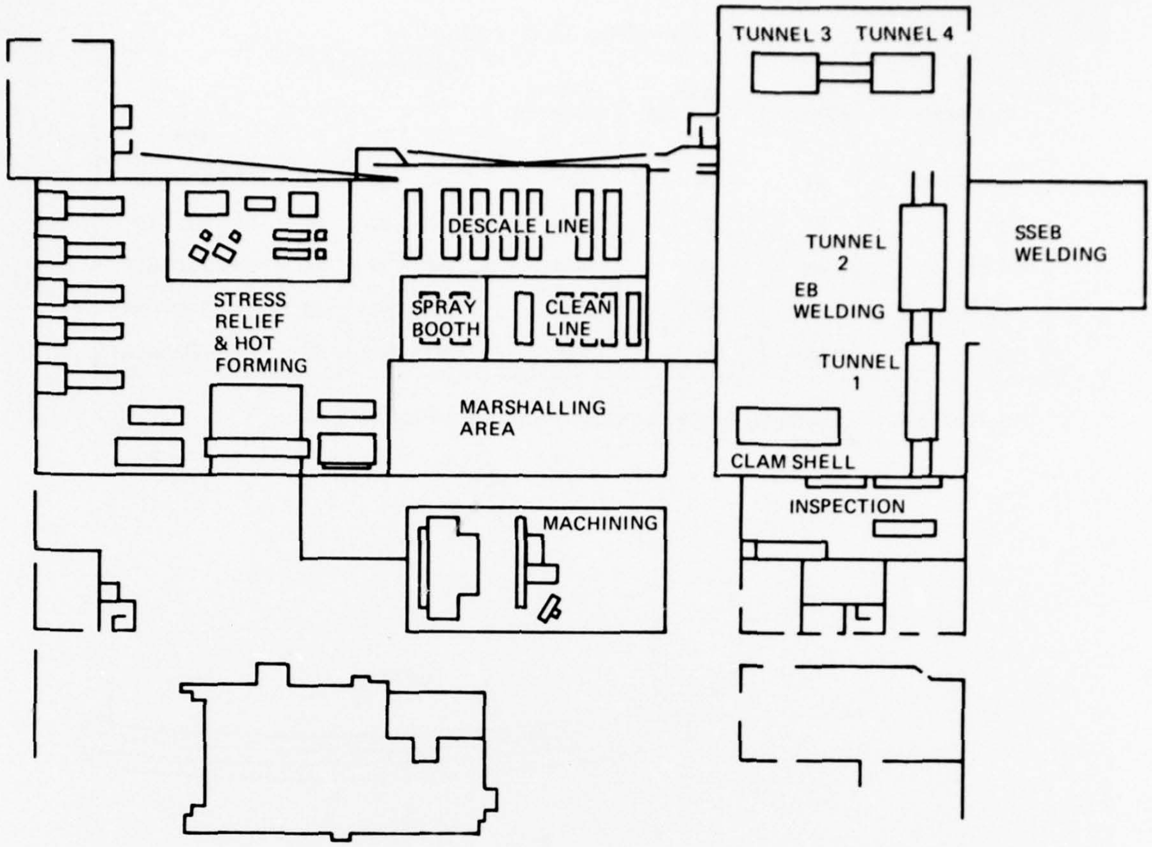


Fig. 4 Electron-Beam Welding and Related Facilities

Fig. 5 Grumman EB Welding Facility

Table VI EB Welding Chamber Capacities

CHAMBER TYPE	MAX. POWER, kw	MAX. VOLTAGE, kv	APPROX. CHAMBER vol, ft^3	GUN MOBILITY, in. X	Y	Z	USE
CLAMSHELL	30	60	2680	310	68	12	PRODUCTION
TUNNEL 1	30	60	2480	242	70	54	PRODUCTION
TUNNEL 2	45	60	2980	300	70	54	PRODUCTION
TUNNELS 3 & 4	30	60	930	114	53*	36	PRODUCTION
BOX	30	60	83	41.5	24*	16.5	DEVELOPMENT

*GUN STATIONARY; MOBILE TABLE PROVIDES Y-MOVEMENT OF PART

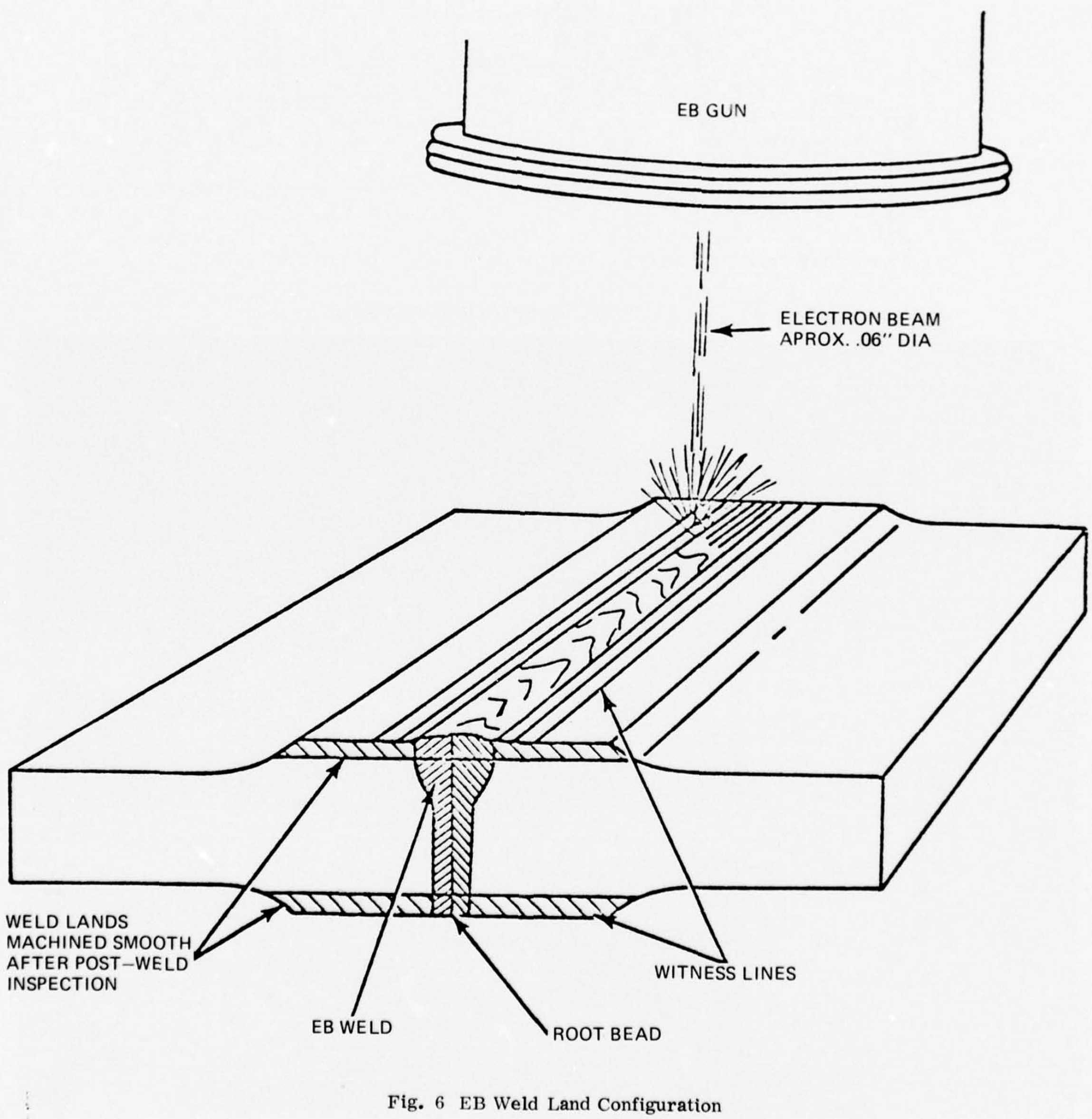


Fig. 6 EB Weld Land Configuration

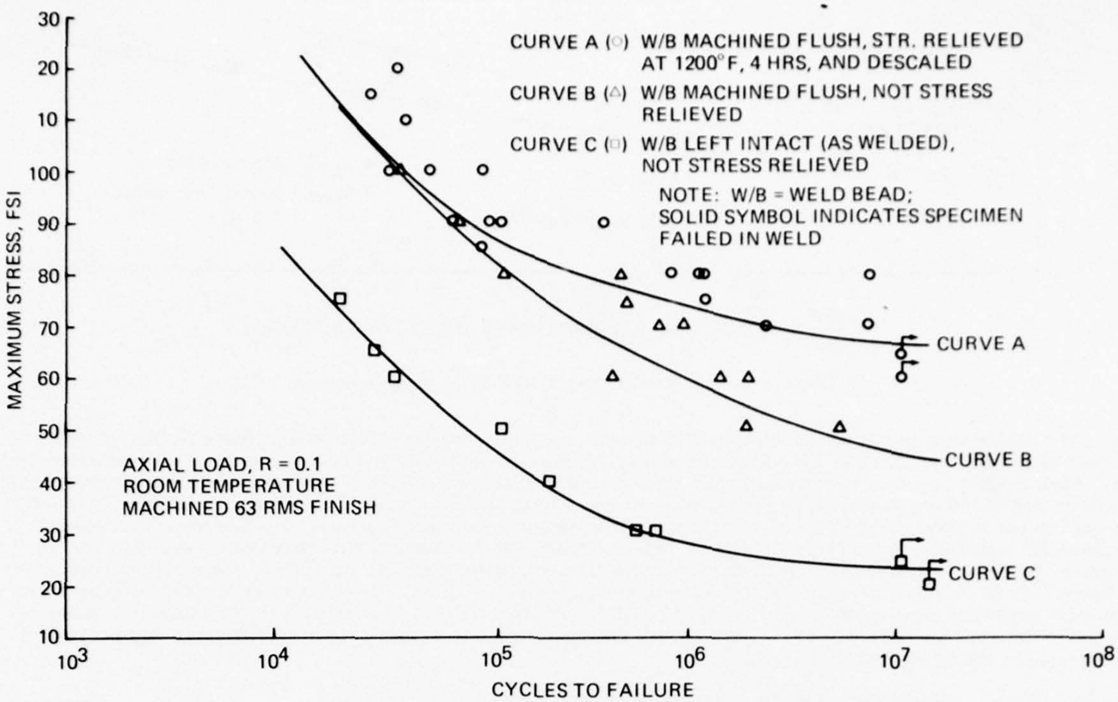


Fig. 7 EB Welded Ti-6A1-4V Ann. Plate-Weld Perpendicular to Loading

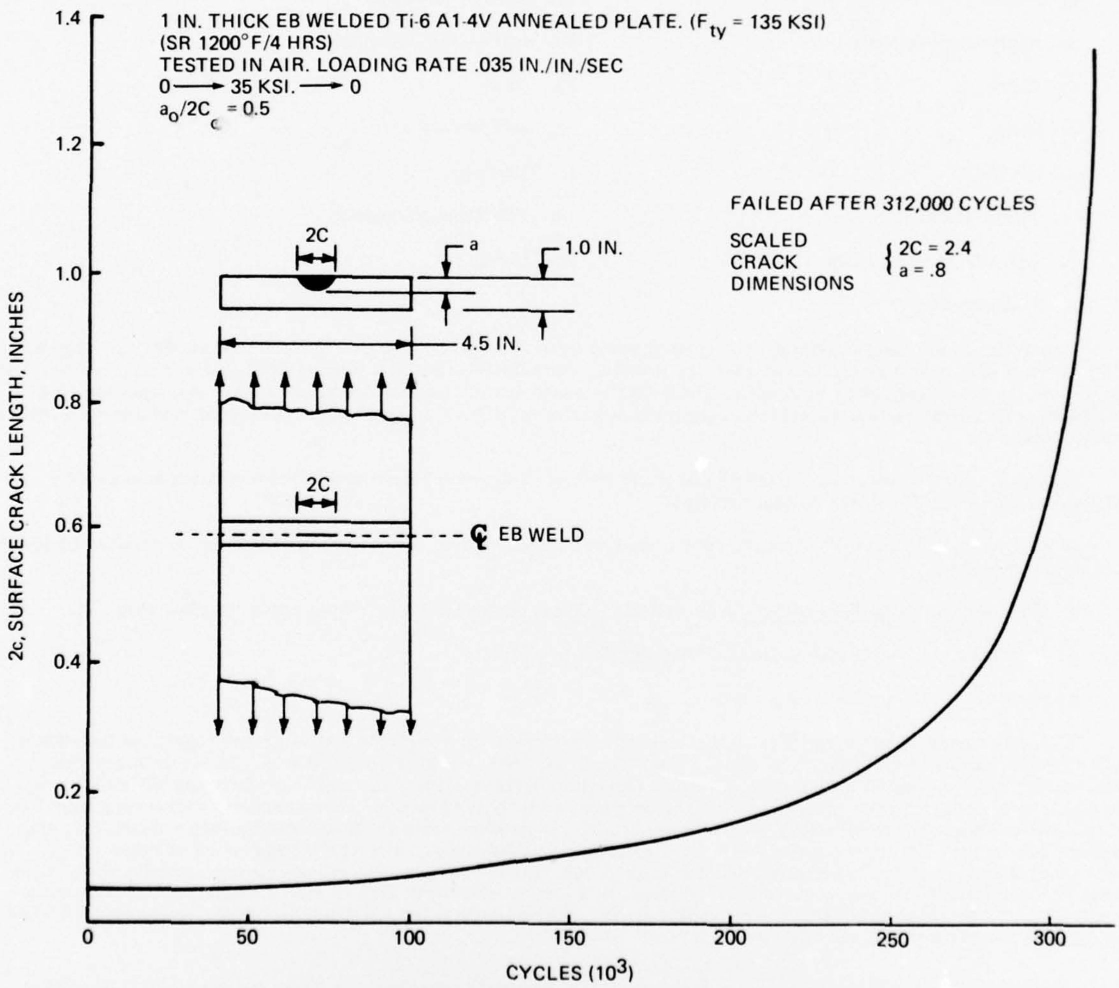


Fig. 8 Constant-Amplitude Surface Flaw Growth Data

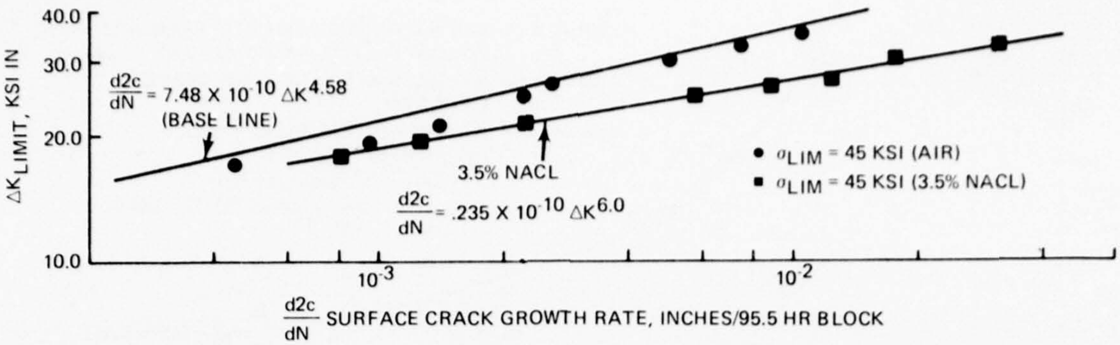


Fig. 9 1-Inch EB Welding Ti-6-4 F-14 Wing Spectrum

The center wing box is essentially manufactured in modular construction from four basic boxes. Starting at the left end of the box, there is LH outboard module, LH inboard module, RH inboard module and RH outboard module. Each module is initially fabricated from its own bottom plate, side plates, end plates and rib stiffeners. Because the top of the box is welded on last, initial module joining includes inboard-to-outboard modules. The left side of the box is then joined to the right side of the midpoint transverse centerline. The top covers are then sequentially installed. Since forgings have become available, the number of welds have been reduced to 70. Of these, 52 welds are greater than one-inch thick and eight are greater than 1.9-in. thick. The smallest gage is 0.580-in. thick. It takes 25 setups to fabricate each wing center-section. All electron-beam welds employ start and stop tabs integrally attached to the part, where possible, to avoid defects associated with starting and stopping of the weld. Integral tabs are essential, particularly for deep welds, to assure proper solidification and prevention of bursts near the finish-end of the welds.

The operational sequence for production weldments is:

1. Prefit
2. Apply witness lines
3. Clean
4. Setup
5. EB weld
6. Visual inspection
7. Witness line inspection
8. Machine weld
9. X-ray inspection
10. Ultrasonic inspection
11. Clean
12. Stress relieve
13. Descale
14. Penetrant inspection
15. Clean

Upper and lower wing covers are fabricated using essentially the same procedures. However, the wing plank is hot formed to a moderate curvature prior to welding. The initial weld in a typical wing cover is a relatively short one joining the pivot section to an actuator piece on the inboard wing cover. After removal of end tabs and final machining, the inboard cover is welded to the outboard cover. Figure 10 shows this weld being made and the related tooling required.

To date, over 150 wing center boxes and many sets of wing covers have been EB welded and accepted by quality assurance for flight and as test articles.

In addition to the above F-14 work, Grumman has also EB welded the following initial major structures for the companies indicated:

- Messerschmidt-Bolkow-Blohm - Multi-Role Combat Aircraft (MRCA) wing center section (Fig. 11)
- Boeing-Vertol - UTTAS Helicopter swashplates (Fig. 12)
- Dassault - Mirage G8A wing panel.

The uniqueness of EB welding is easily shown if we consider a weld joint that is greater than one inch thick and is heavier on one side of the joint than on the other side. How would you weld it to produce minimum weight, cost, shrinkage and distortion? Figure 13 shows the joint design choices you would have between EB welding and the major arc-welding processes presently available for production welding of heavy sections with a minimum number of weld passes. EB welding is the only process that can produce the weld in the configuration denoted by the solid outline in Fig. 13 without adding additional metal in the joint area. A typical requirement of other processes for a welding groove is depicted by the dashed lines in Fig. 13. Costs are also increased significantly when filler metal and shielding gases are required for-welding such joints. Contamination is also a danger when welding out-of-chamber. The EB process is self-correcting in this respect, since the EB gun will automatically shut off when the vacuum pressure in the chamber exceeds about 10^{-3} torr.

Figure 14 shows that the major cost factors in most welding processes are labor and overhead. The filler metal and protective gas requirements, however, can also increase costs significantly, particularly when welding joints greater than 1/4-in. thick.

Fig. 10 EB Welding F-14 Wing Cover to Pivot Lug

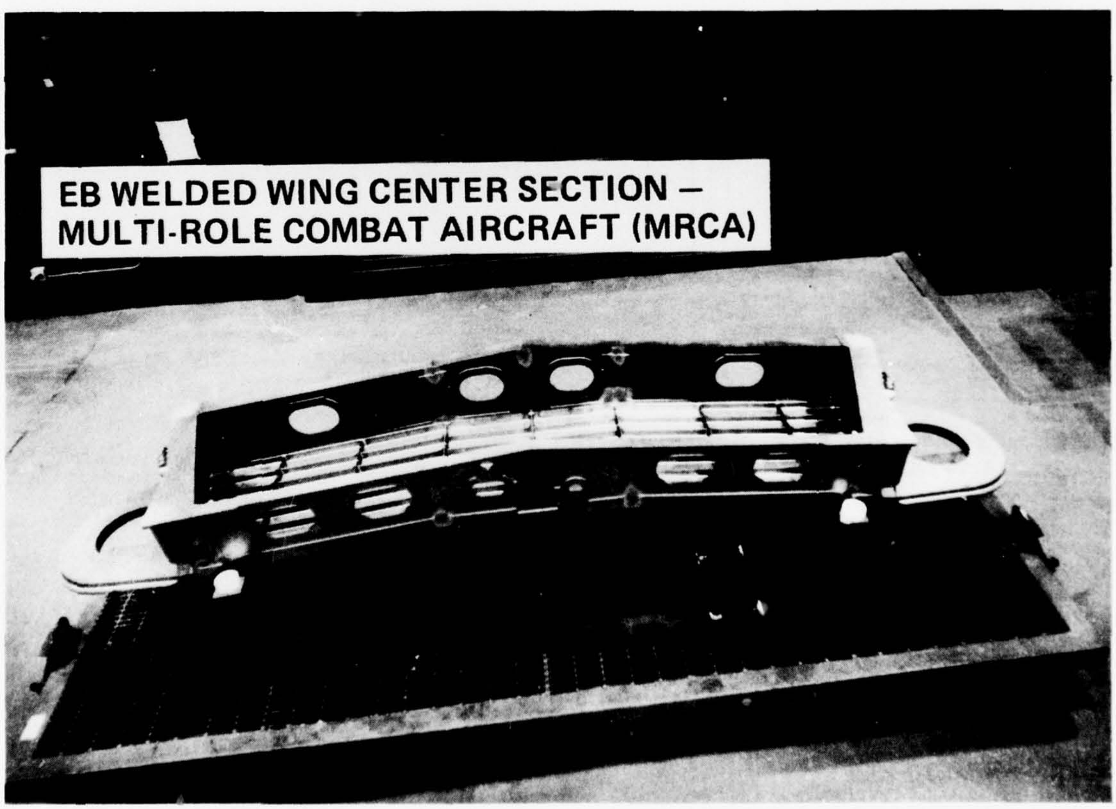


Fig. 11 EB Welded Wing Center Section - Multi-Role Combat Aircraft (MRCA)

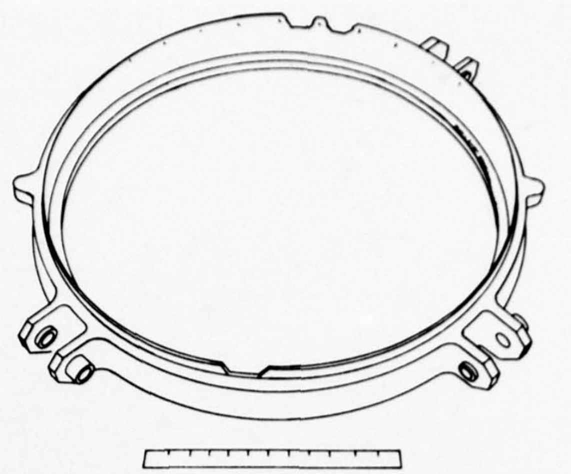


Fig. 12 Boeing-Vertol UTTAS Helicopter Swashplate

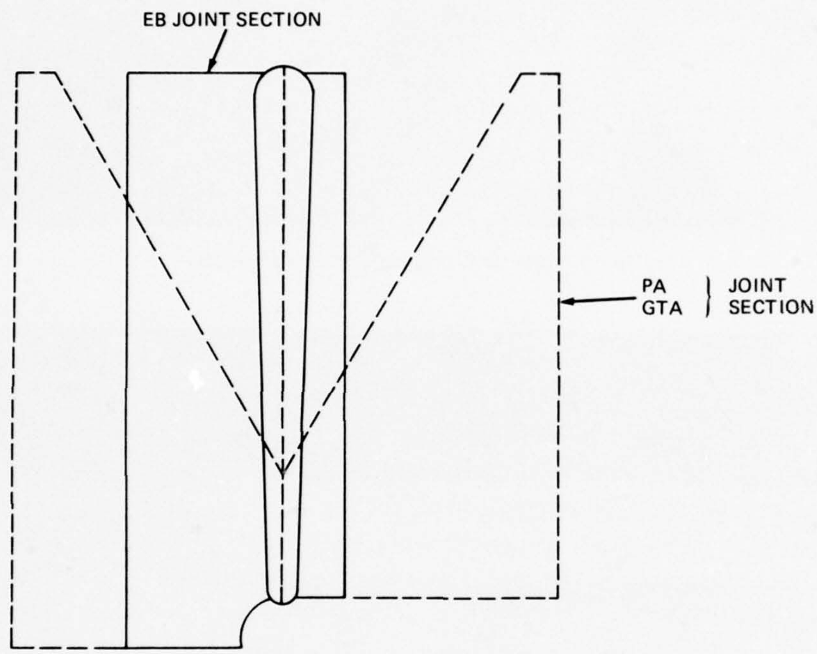


Fig. 13 Schematic Comparison of EBW Straight Butt Joint with V-Groove Joint Necessary for Arc Welding

WELDABILITY OF BETA TITANIUM ALLOYS

A study (Ref. 1) was conducted recently to establish welding methods for two advanced titanium alloys which are promising candidates for future aircraft welded construction. The alloys investigated were of the beta type and are designated as Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C) and Ti-8Mo-8V-2Fe-3Al (Ti-8-8-2-3).

Welding techniques and parameters were developed for pulsed gas-tungsten-arc welding 0.1-in.-thick Beta C; plasma-arc welding 0.1-in. and 0.5-in.-thick Beta C and 0.5-in.-thick Ti-8-8-2-3; and electron-beam welding of 0.5-in.-thick Beta C and Ti-8-8-2-3 and 1.0-in.-thick Beta C. In addition, weld shrinkage and distortion, gap allowables (with and without filler wire), and weld repair procedures were evaluated. Since both the Beta C and Ti-8-8-2-3 alloys must be aged for greater strength, heat treatment cycles were evaluated to attempt to optimize the alloy and weldment ductility and toughness in the 150 to 170-ksi range. Both partial-age-weld-partial-age and weld-plus-age cycles were evaluated. The optimum heat treatment cycles for each alloy/thickness combination consisted of post-weld ages as follows:

- 0.1-in.-thick Beta C: 1100°F for 3 hr
- 0.5-in.-thick Beta C: 1050°F for 8 hr
- 1.0-in.-thick Beta C: 1030°F for 8 hr
- 0.5-in.-thick Ti-8-8-2-3: 1000°F for 24 hr.

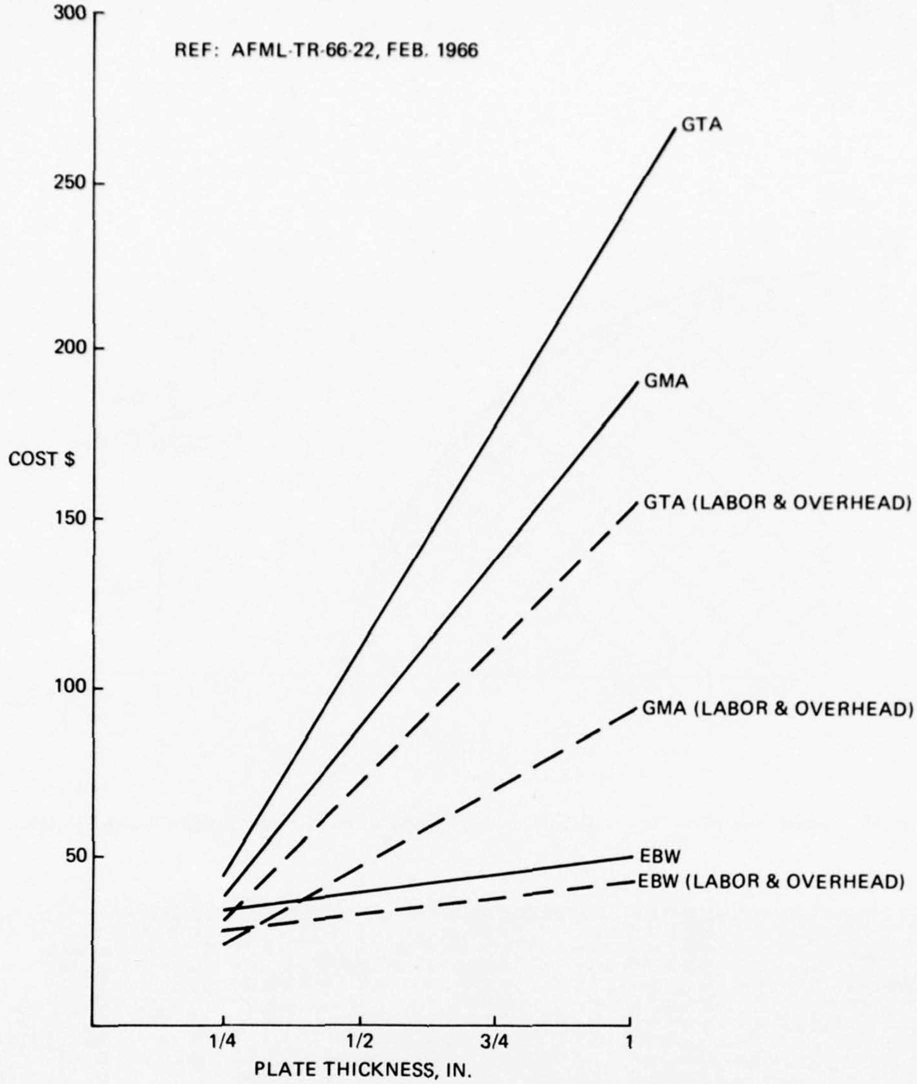


Fig. 14 Process Cost for Welding Maraging Steel (18Ni-8Co-5Mo) 24" Diam. Cylinder - Two Heads/Cyl.

Weldment property evaluation of optimally heat treated Beta C and Ti-8-8-2-3 for each weld process/thickness combination included tensile, fatigue, fracture toughness and stress corrosion testing.

The best combinations of yield strength, ductility and toughness, as well as fatigue endurance strength, were obtained in plasma-arc and electron-beam welded 0.5-in.-thick Ti-8-8-2-3. Plasma-arc welded Ti-8-8-2-3 exhibited 168.7 (average) ksi yield strength with 3.5% elongation and 60 ksi fatigue endurance strength, while electron-beam welded 0.5-in.-thick Ti-8-8-2-3 exhibited 165 (average) ksi yield strength with 7% elongation and 55 ksi fatigue endurance strength. Fracture toughness values for plasma-arc and EB welded Ti-8-8-2-3 were 38-45 ksi $\sqrt{\text{in.}}$ and 55-58 ksi $\sqrt{\text{in.}}$, respectively (Fig. 15).

As a result, both the plasma-arc and electron-beam welding processes were selected to weld a Ti-8-8-2-3 subscale airframe component to permit further comparisons between the processes. The subscale component selected was an F-14A wing pivot actuator-to-cover splice joint. Components were successfully welded with both welding processes. Constant-amplitude tension-tension fatigue testing of specimens removed from the subscale components yielded fatigue endurance strengths of 60 ksi for plasma-arc welding and 65 ksi for EB welding. In both cases, properties equalled or exceeded parametric results.

These results indicate that for statically critical joints the beta alloys offer significant promise as electron-beam or plasma-arc weldments. For fatigue-critical joints, the alpha-beta alloys still afford better strength levels.

SLIDING-SEAL ELECTRON-BEAM WELDING

In the early part of this decade the Air Force sponsored a program at Grumman on Sliding-Seal Electron-Beam (SSEB) Welding. (Ref. 2). The SSEB welding system utilized in this program (Fig. 16) was designed and manufactured by Sciaky Bros., Inc., under Air Force contract. This unit consists of a portable, vacuum, moving EB welding head mounted on a ram manipulator, backup tooling, and associated power supply and controls. The power capacity of this unit is 30 kw (60 kv, 500 ma) and is capable of welding at vacuum pressures ranging between 1 x 10^{-4} torr and 100 Hg. The backup-table vacuum pressure is maintained between 10 and 50 μ Hg. The vacuum in the moving welding head is obtained by pumping between two silicone rubber vacuum seals (in the head) that ride on the workpiece being welded.

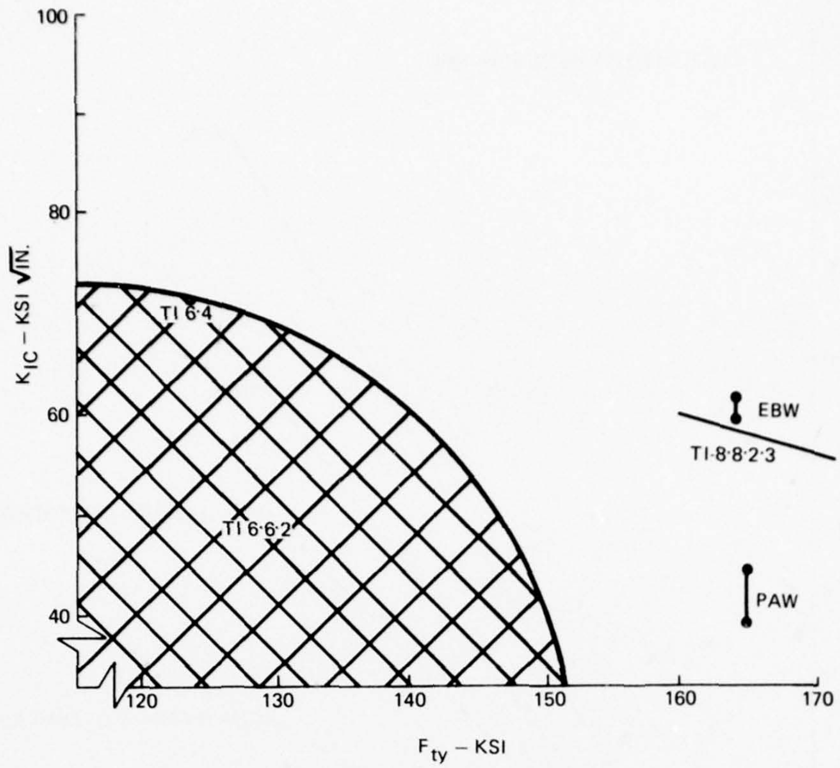


Fig. 15 Comparison of K_{ic}/F_{ty} - Program Beta Alloys With Ti-6A1-4V and Ti-6A1-6V-2Sn.

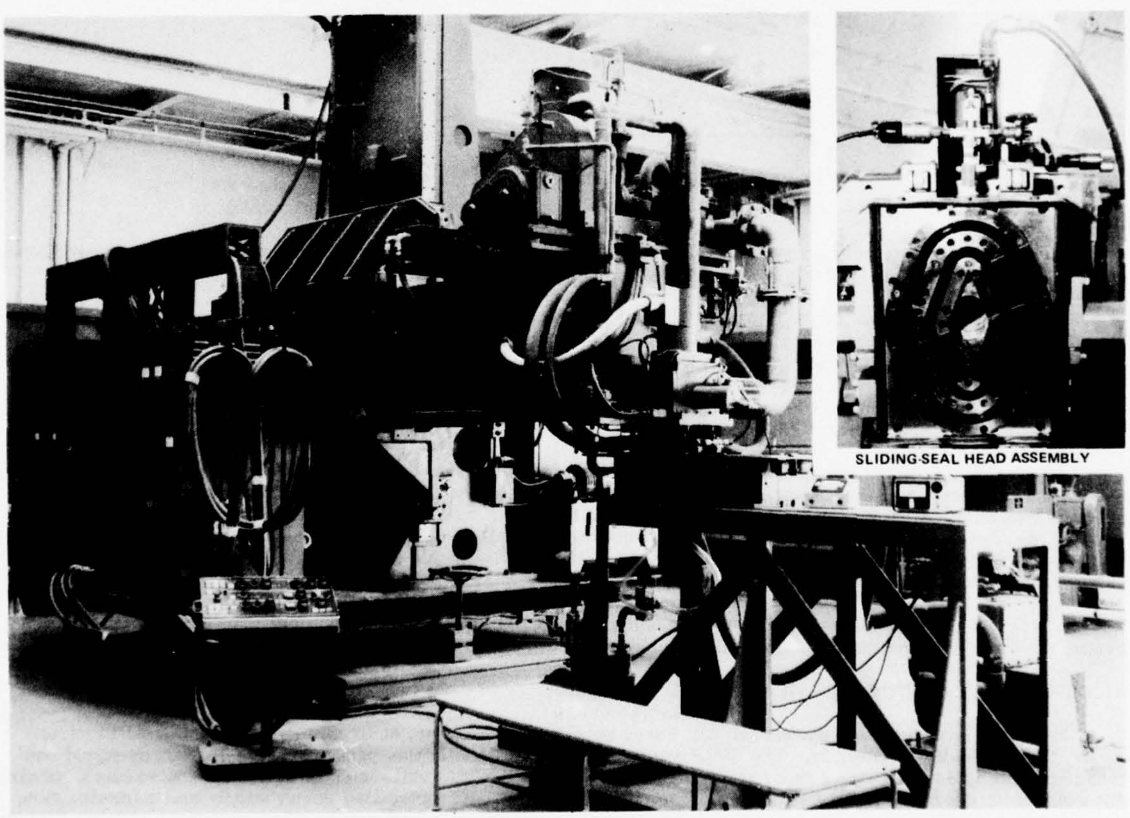


Fig. 16 Sliding-Seal Electron-Beam Welding Equipment

The ram manipulator, which supports the welding head and associated vacuum pumping equipment, is capable of traversing a distance of 6 ft in the flat position (X-axis) and 5 ft in the vertical position (Z-axis). The vacuum-sealed backup tool is capable of being used in the flat position or remounted in the vertical position. Use of the SSEB welder permits welding of large aerospace structures that cannot be welded in available chambers. The ram-manipulated boom and column assembly is mounted on a rotatable base, which provides 360-deg rotation about the Z-axis. This rotation permits positioning of the local welding chamber over the joint to be welded and welding in more than one quadrant. The EB gun, local welding chamber and associated vacuum pumping equipment are mounted on the end of the boom to reduce the length of the pumping lines.

The SSEB welder was installed at Grumman in a production plant area adjacent to the EB welding facility. The SSEB welding equipment was used to establish optimum welding parameters for square butt joints made from 0.250-, 0.500-, 0.750-, and 1.00-in.-thick 2014-T651 aluminum alloy plate and annealed Ti-6Al-4V alloy plate, and 1.00-in.-thick HY-130 steel alloy plate. Seal reliability, filler metal addition, repair weldability and proper seal-pass techniques were determined and verified for subsequent efforts to extend the SSEB welding process to production hardware. Tensile, fatigue and fracture toughness data were obtained on typical square butt welds in the above thicknesses made by flat and vertical welding techniques. All weldments were non-destructively tested by radiographic, dye-penetrant and ultrasonic methods. Metallographic results were correlated with mechanical properties.

The SSEB welding equipment was also used to demonstrate its capability to fabricate a simulated structural component - a stiffened titanium wing skin panel. The welded panel was subjected to fatigue tests under simulated loadings for advanced fighter aircraft structures. The panel was also evaluated for repair capability, weld penetration, surface and underbead appearance, shrinkage and distortion. Weld soundness of the panel was determined by radiographic, dye-penetrant and ultrasonic inspection techniques. All test results were tabulated, reviewed, analyzed and compared with results available on similar structural components welded in the large, Grumman EB welding chambers and on gas-tungsten-arc (GTA) or gas-metallic-arc (GMA) equipment.

The status of the SSEB welding equipment at the conclusion of the program can be summarized as follows:

- Aerospace-quality, flat butt panels up to 2 ft in length are fabricable from:
  - 1/4- to 1-in.-thick 2014-T651 aluminum alloy plate
  - 0.190- to 0.940-in.-thick Ti-6Al-4V titanium alloy plate
  - 0.440-in.-thick HY-130 steel alloy plate
- Optimized SSEB welding parameters are similar to hard vacuum EB welding parameters for Ti-6Al-4V titanium and 2014-T6 aluminum alloy
- Tensile, fatigue and fracture toughness values obtained for SSEB butt welds are comparable to production EB weld properties for Ti-6Al-4V titanium alloy
  - Tensile fatigue joint efficiencies = 100% of base metal
  - Fracture toughness (K_{IC}) = 39.0, minimum, for base metal having F_{ty} = 55.4 ksi
- GTA butt joint seal welding prior to full-penetration SSEB welding produced porosity-free welds in all alloys and thicknesses used in this program
- Penetration in SSEB welds can be obtained readily in thicknesses up to:
  - 2.0 in. for 2014-T6 aluminum alloy
  - 1.5 in. for Ti-6Al-4V titanium alloy

  Heavier gages are feasible for short welds (up to 2 ft long)
- Tensile and fatigue strengths for SSEB welded 2014-T6 aluminum alloy are comparable to EB hard vacuum welds
  - Tensile joint efficiency = 75-80% of base metal
  - GTAW joint efficiency = 65% of base metal
  - GMAW joint efficiency = 60% of base metal
- K_{IC} fracture toughness of SSEB welds in 2014-T6 aluminum alloy requires thicknesses greater than one inch for valid data acquisition
- SSEB welding of 2014-T6 aluminum alloy at speeds greater than 60-80 in./min degrades mechanical properties and can result in transverse cracks at the fusion line and in the weld bead
- Welds were limited to 2 ft by fixture size and boom travel distance.

A follow-on contract for SSEB welding (Ref. 3) was directed to provide the process with more flexibility for a variety of applications. Particular attention was given to long-length flat welds, large cylinder welds, special joint configurations (e.g., tees) and the welding of an actual airframe part. A preheat welding chamber was also evaluated for crack-sensitive steel welding.

First, a long flat-plate welding fixture (Fig. 17) capable of welding plates up to 13 ft long with a stationary SSEB gun and moving part-piece was evaluated for welding aluminum and titanium alloys. A GTA sealing pass was employed to maintain the vacuum when EB welding full-penetration passes. Seal wear was no problem with aluminum alloys and hundreds of feet were welded. However, for titanium alloys, only one to two plates could be welded before seals had to be changed. This was primarily caused by crown on the weld bead and heat.

A special shapes small chamber was next evaluated for butt welding tee-shapes as shown in Fig. 18. A weld was made through a $3\frac{1}{2}$-in.-long slot in the cover which was completely contained within the sliding seals on the gun during the entire length of the weld (about 3 in.). To make the second weld in the tee, the pieces were rotated ninety degrees to weld in the down-hand position. Both aluminum and titantium tees were readily welded. The molded RTV silicone rubber seals performed with no problems and vacuums around 10 to 20 torr were readily obtainable with no leaking around the shapes.

Welding was also successful at temperatures of 200°F to 450°F on HY130 and D6AC high-strength steels. Figure 19 shows the welding setup with the variac power control and temperature recorder with the sliding seal in position for welding. No problems on seal wear or sticking on heat-up were experienced. The top cover was aluminum in this case and its thermal diffusivity apparently is optimum for this kind of welding. Temperature stability of the heat-up is excellent. With the heater power off, the temperature drop from 250°F was about 10-15 deg in an hour. Some lead shielding was provided in the sealing areas to prevent radiation exposure which was monitored by the Safety Department.

As a conclusion to this program, an F-14A Wing Closure Beam (a production part) was selected for SSEB welding to demonstrate capability to used airframe parts. A fabricated vacuum chamber was set up on the flat weld table/rail assembly and was successfully used to produce 9-ft-long welds joining two Ti-6A1-6V-2Sn alloy L-extrusions to produce five wing beams (Fig. 20). One radiographically sound wing beam was used to determine mechanical property data. Tensile efficiency was 100% with all weld failures in the parent metal. Fracture toughness for welds was 27.5 ksi $\sqrt{\text{in.}}$ compared to base metal at 45.4 ksi $\sqrt{\text{in.}}$ Fatigue endurance was at 55 ksi, lower than expected. It was later found that a change in the cleaning procedure would eliminate very small-diameter pores near the surface which were not detected and apparently led to early failures in fatigue.

In general, it can be concluded that sliding-seal or other mobile welding systems should see increasing applications in the next decade if welding is used significantly on aircraft. Reports from other industries such as marine and nuclear certainly indicate that, even if the aerospace industry does not use the process, it will still be used elsewhere.

PLASMA-ARC WELDING

Plasma-arc welding (PAW) is similar to both GTA and EB welding, but also maintains several unique characteristics. Though it is basically an arc-welding process, it is unusual in that the primary heat input is due to a constricted plasma column created by the arc between the tungsten electrode and the workpiece and directed against the latter. Because of this constriction, greater energy concentration, higher velocity and higher temperatures are available in PAW than in other arc processes. In addition, keyhole welding, which is similar to full-penetration EB welding, can be accomplished. The plasma-arc weld thus has a characteristically high depth-to-width ratio with a uniform underbead.

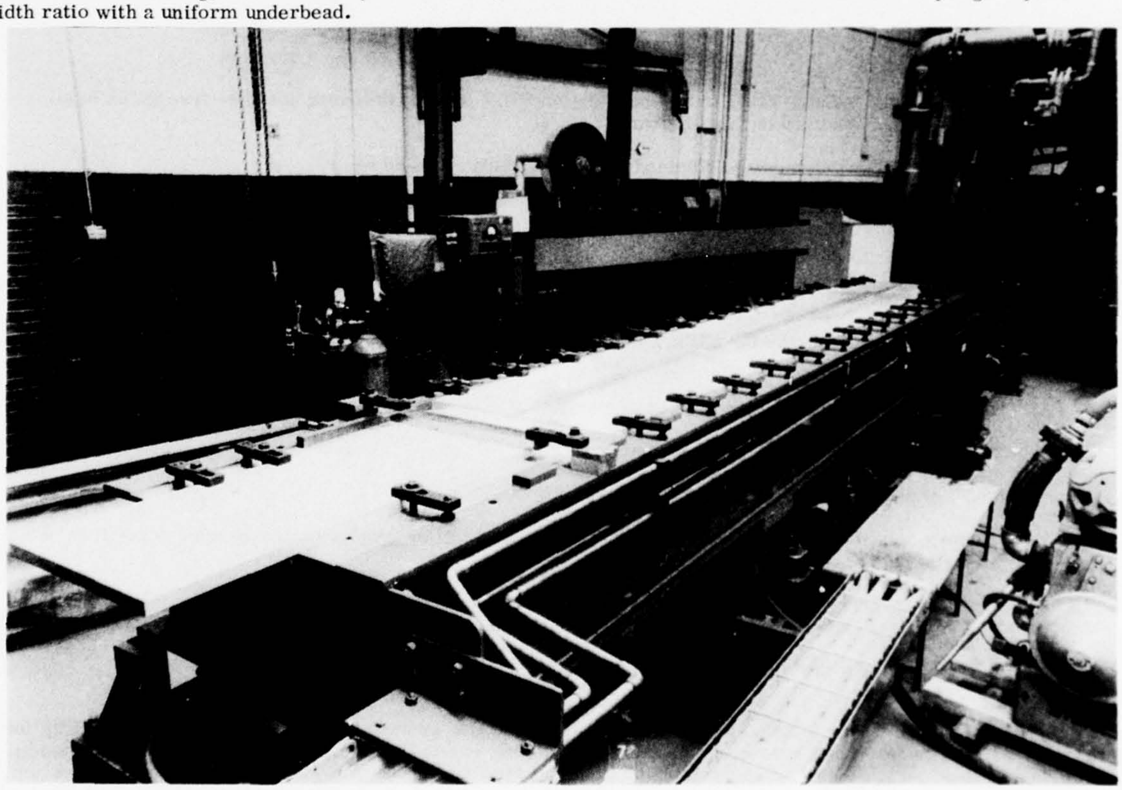


Fig. 17 Flat Plate Welding Fixture Setup for 12-ft-long Aluminum Butt Weld

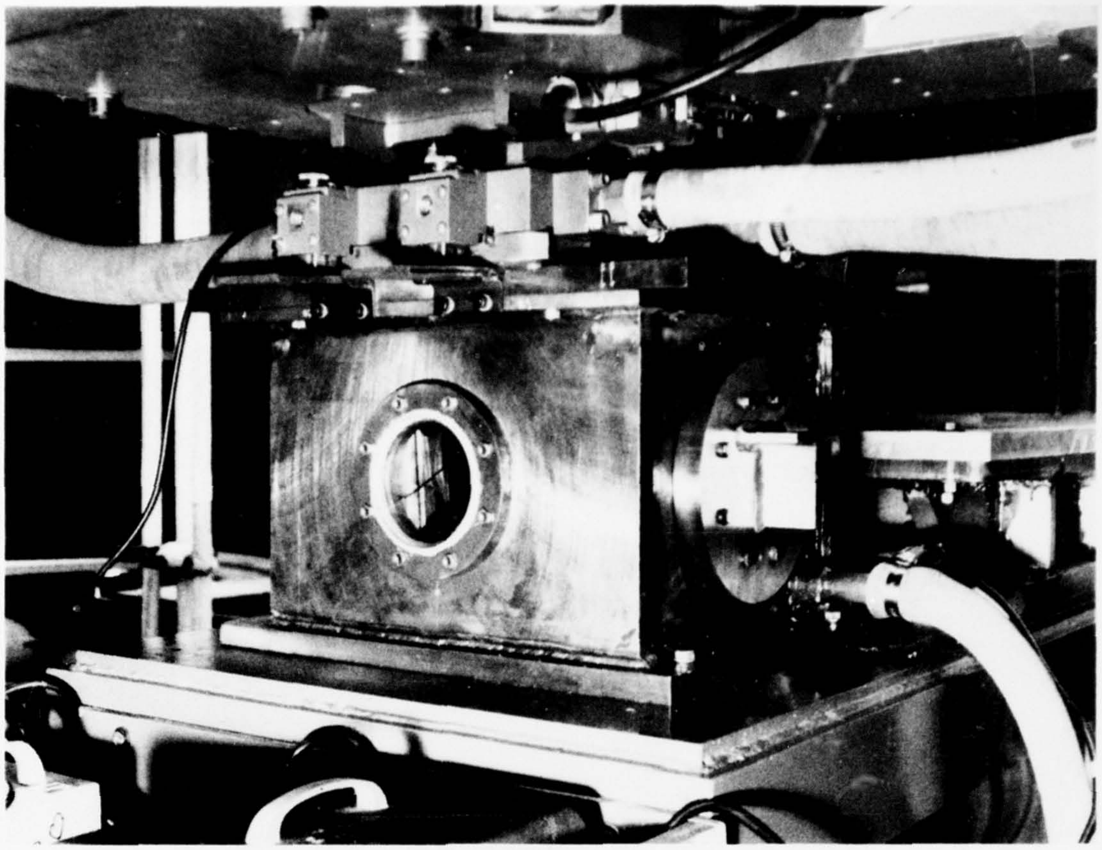


Fig. 18 Special Shapes Weld Fixture Setup for Top Weld on Tee Angle

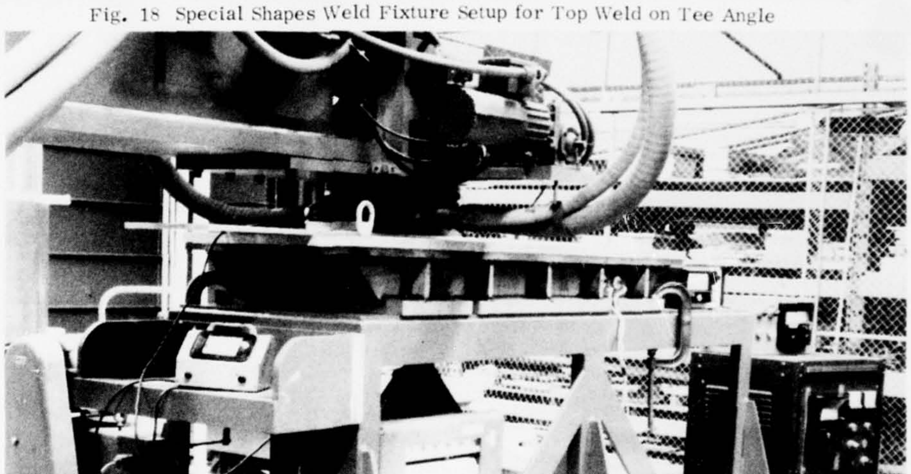


Fig. 19 Preheat Steel Welding Fixture Setup Showing Variac Power Control and Strip Chart Recorder

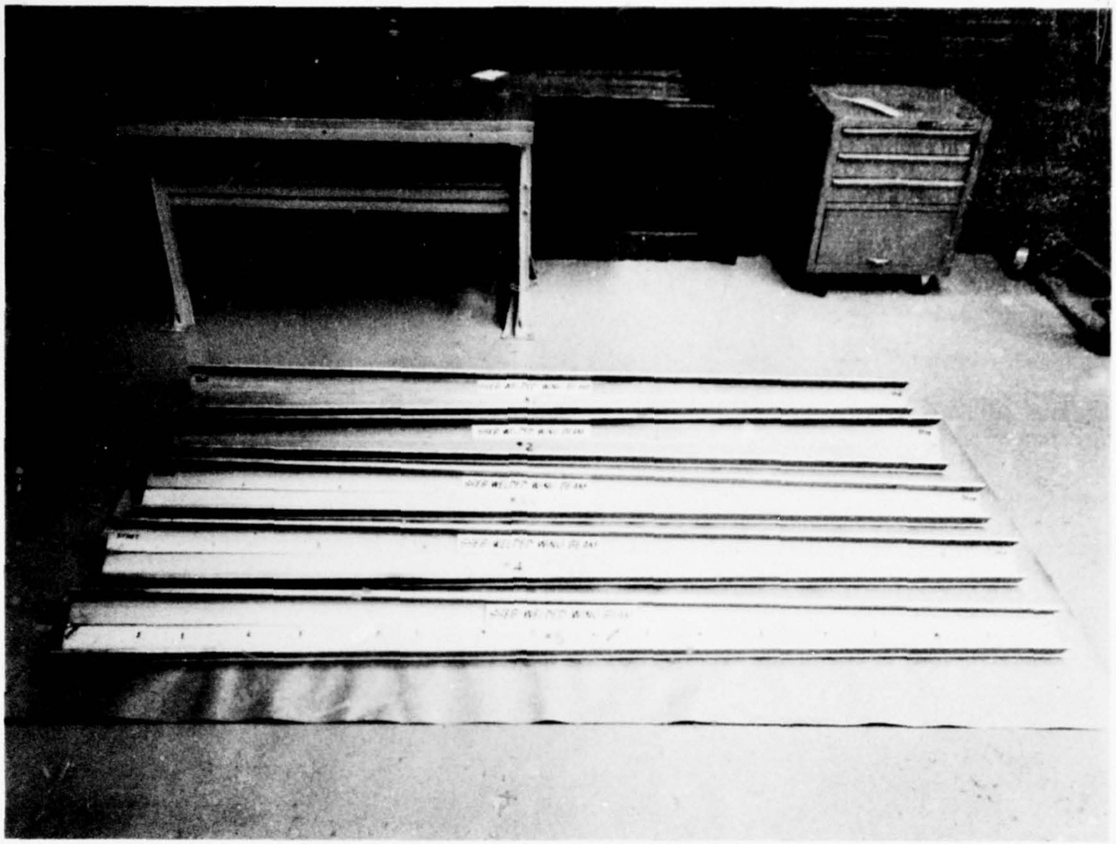


Fig. 20 Five, 9-Foot-Long, SSEB Welded Wing Beams

Figure 21 shows schematically the arrangement to produce the constricted arc and the important variables. Around the central electrode is an orifice gas tube. The constriction at the bottom end is normally referred to as the nozzle end. It is extremely important that the electrode be centered very accurately to prevent loss of maximum penetration capability.

Also under certain conditions the plasma-arc is interrupted from the transferred-mode to what is known as double-arcing (*i.e., the arc is transferred to the outer gas shielding cup shown). This condition is troublesome in* welding thick plate, but has been controlled by using non-metallic out-gas cups. Modification of the nozzle shape has also helped to alleviate this problem in making welds up to one inch thick in a single pass.

Figures 22 and 23 show trailing shield arrangements that have been used to successfully weld titanium 1/2-in. thick or more. The bulkier arrangement in Fig. 22 provides viewing ports and a manometer for monitoring the internal positive pressure of the gas blanket. Tables VII and VIII give the advantages and disadvantages of plasma-arc welding versus gas-tungsten-arc and electron-beam welding.

Figure 24 shows a weld produced in 0.923-in.-thick titanium plate in a single pass which was an objective of an Air Force program (Ref. 4). A gap about 0.060 in. is necessary prior to welding with filler wire. Shrinkage in the joint is 0.050 in. For EBW a comparable joint shrinkage about 0.015 in. occurs.

It has been reported (Ref. 5) that as a result of this work PAW has been applied to welding the Ti-6A1-4V upper cover on the B-1 wing carry-through structure. There are eight joints per aircraft around 5 ft long and 1/2 in. thick. It is estimated that the following cost reductions are obtained versus GTAW: joint preparation (75%), setup (80%), welding (85%), inspection (67%), filler wire (90%), facilities (0%).

In the work mentioned previously on the beta titanium alloys, costs were compared for plasma-arc and electron-beam welding a hypothetical aircraft wing joint in a production run of 1000 units. The joint was 1/2 in. thick single butt and 38 in. long. The analysis showed that costs of the two processes are quite similar. While the capital equipment cost of PAW is lower, a higher tooling cost is required both to shield the weld in arc and to resist distortion due to the greater propensity of PAW for shrinkage and distortion. A slower production rate is reflective of both the longer set-up and weld times. The saving which might be achieved by the somewhat lower tolerance and fit requirements of PA weldments compared to EB weldments was not factored into the analysis. On the other hand, the more extensive postweld straightening, which PAW would probably require, was not accounted for either.

It was concluded that, in view of the small difference in predicted costs between PAW and EBW, it is likely that a decision on which welding process was to be used for a particular joint would be more significantly determined by other factors.

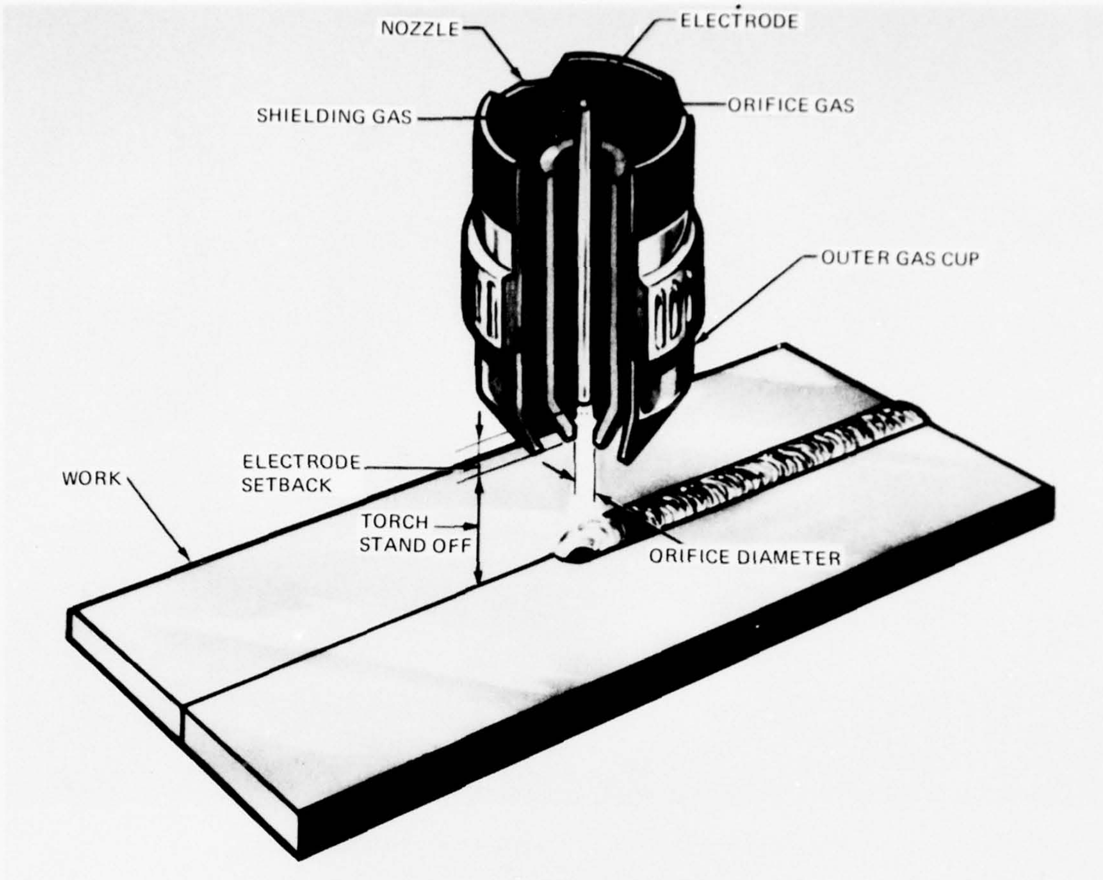


Fig. 21 Plasma-Arc Torch Terminology

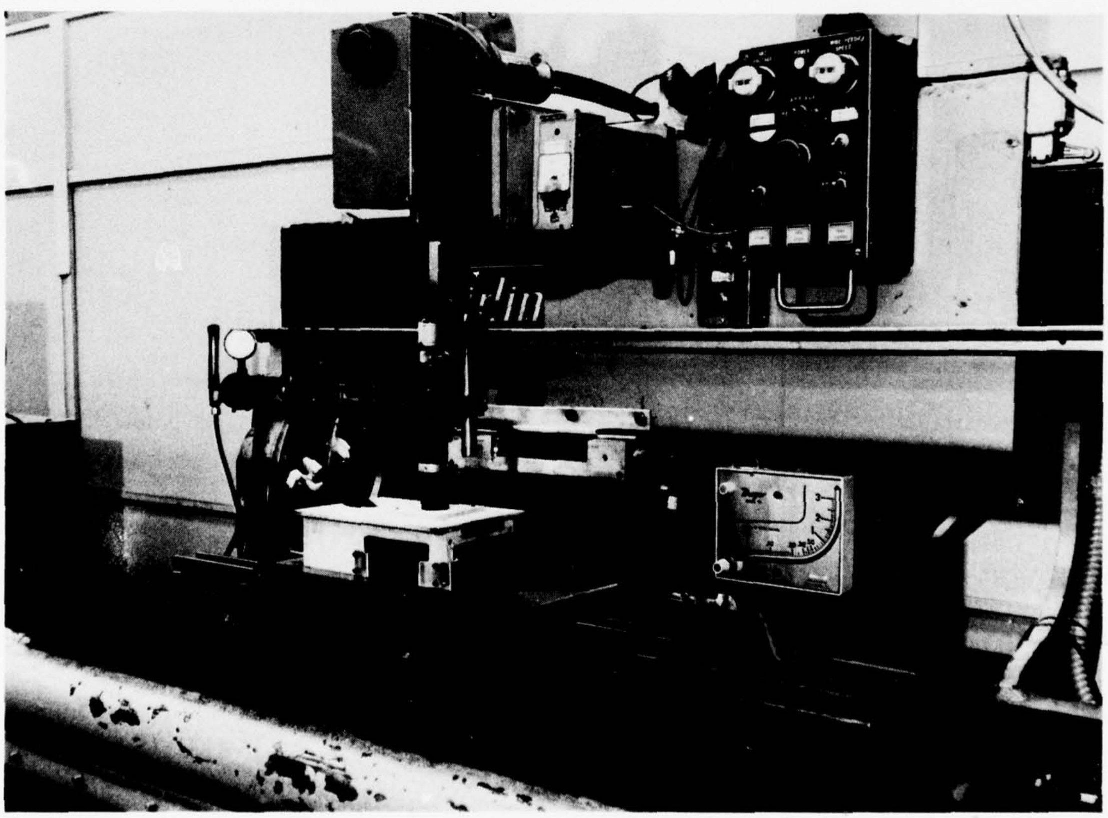


Fig. 22 PAW Shielding Arrangement

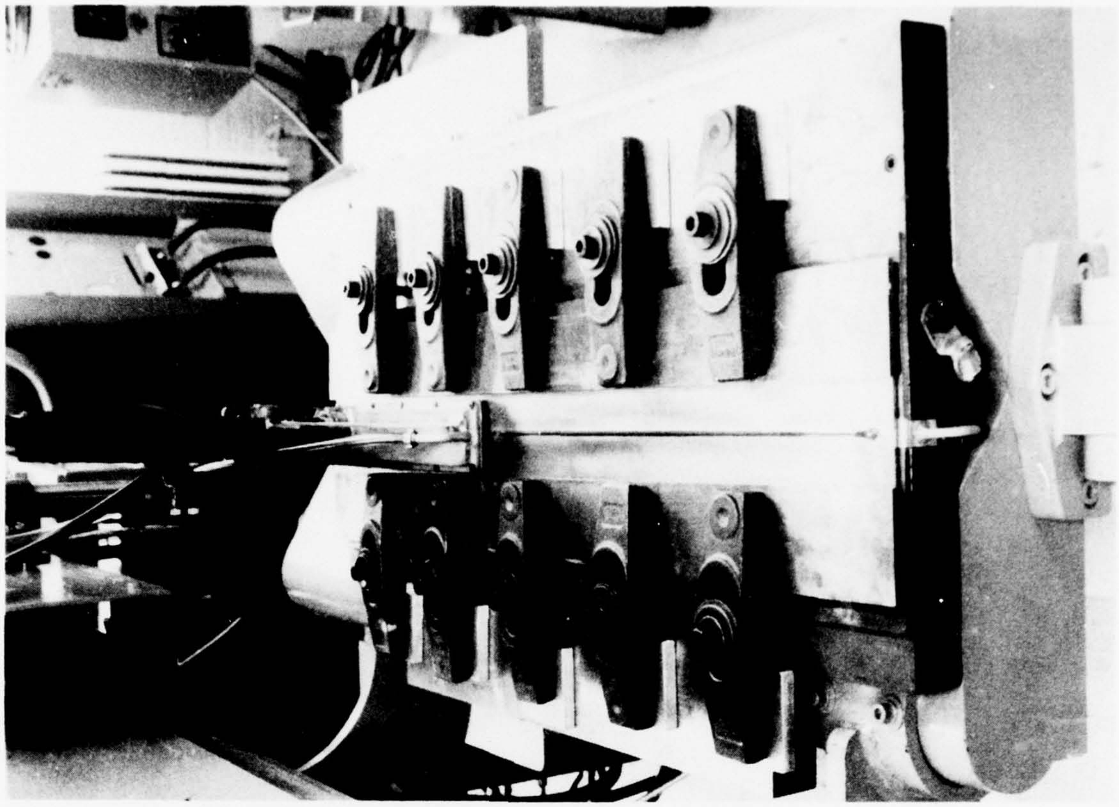


Fig. 23 One-Foot-Long Trailing Shield and Welding Fixture

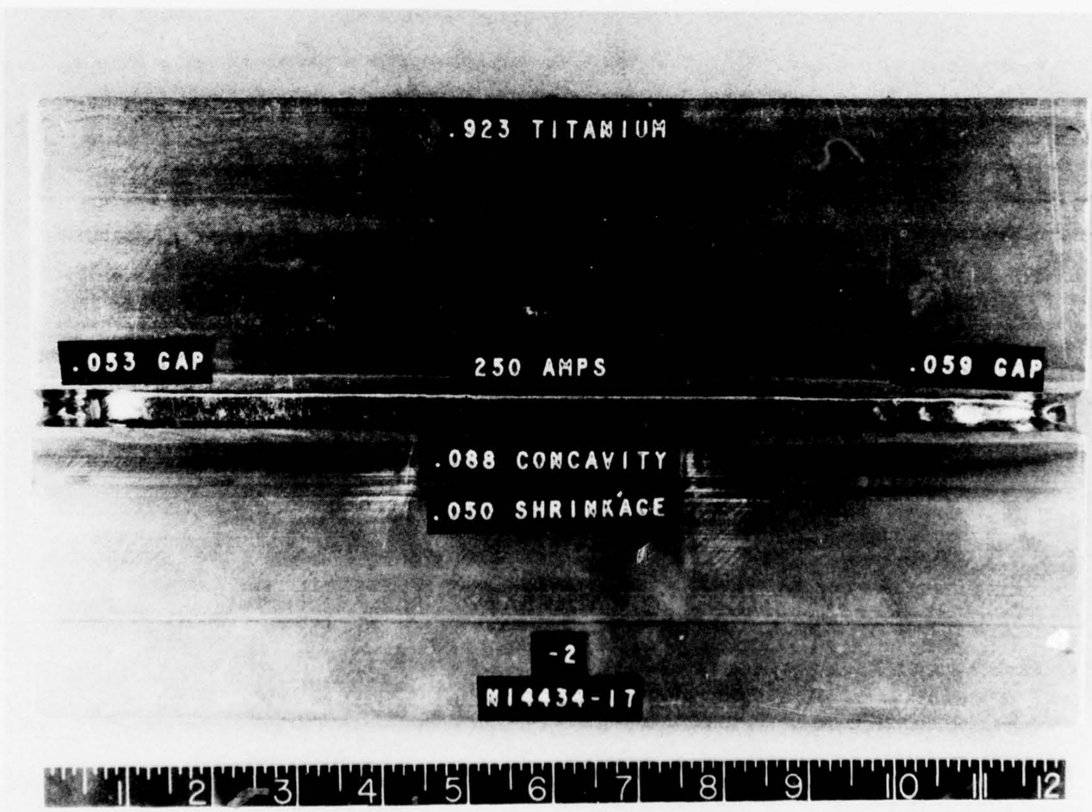


Fig. 24 PAW Single Pass in 0.923 Inch Thick Plate

Table VII Advantages and Disadvantages of Plasma-Arc Welding Compared to Gas-Tungsten-Arc Welding

ADVANTAGES

- CLEANER SURFACES BECAUSE OF THE SHIELDING GAS AROUND THE ARC
- NO TUNGSTEN CONTAMINATION FROM THE ELECTRODE
- GREATER SPEED AT EQUIVALENT CURRENTS BECAUSE OF THE HIGHER ARC CURRENT DENSITY IN THE CONSTRICTED ARC – – ESPECIALLY SO FOR THE KEYHOLE MODE
- LESS CRITICAL STANDOFF, BECAUSE OF LOWER ARC DIVERGENCE AND, THEREFORE, LESS VARIATION IN WELD BEAD WIDTH
- AT VERY LOW CURRENT, THE PLASMA-ARC IS MORE STABLE THAN THE GAS-TUNGSTEN ARC
- UP TO 50 PERCENT LESS CURRENT REQUIRED BECAUSE OF GREATER EFFICIENCY
- LONGER USABLE ARC BECAUSE OF LOWER DIVERGENCE
- GREATLY INCREASED PENETRATION IN KEYHOLE MODE; USE OF THE LOWER COST SQUARE-BUTT CONFIGURATION FOR WELDS OVER 1/8-INCH
- NARROWER WELD BEADS; LESS HEAT EFFECT

DISADVANTAGES

- DANGER OF BURN-THROUGH BECAUSE OF HIGHER HEAT CONCENTRATION
- HIGHER EQUIPMENT AND OPERATING (INERT GAS CONSUMPTION) COST
- SHORT ORIFICE LIFE

Table VIII Advantages and Disadvantages of Plasma-Arc Welding Compared to Electron-Beam Welding

ADVANTAGES

- WIDER WELD WITH LESS CHANCE OF MISSED SEAMS
- WELDING PERFORMED OUTSIDE OF VACUUM CHAMBER FOR GREATER ACCESSIBILITY, LOWER COST AND MORE VERSATILITY
- LOWER EQUIPMENT AND OPERATING COSTS

DISADVANTAGES

- HIGHER CONTAMINATION THAN EB VACUUM WELDS
- LOWER WELDING SPEED
- SHORTER SOURCE-TO-MATERIAL DISTANCE
- LESS PENETRATION
- WIDER WELD BEADS; GREATER HEAT EFFECT, DISTORTION

PULSED-ARC TUBE WELDING

Even though the previous discussion indicates that EBW and PAW are replacing GTAW, there is one area where the latter process is very reliable and is generally preferred. Automated GTA welding of tubing began to be used around 1960. Since that time, there have been many advances and applications. Although brazing and cryogenic fittings are both being used on the F-14 aircraft, bench-welded titanium and stainless steel fittings have been used very successfully to weld about 1000 joints per aircraft, ranging from 3/16 in. to 1-1/2 in. in diameter.

Orbital-arc tube welding is another name given to this process because it is more descriptive of the fact that during welding the tungsten electrode around the tube joint to effect the weld in an inert atmosphere. The tubes are held stationary and butted with minmium gaps by means of external clamps (Fig. 25).

A number of other applications for automated GTA tube welding have been mentioned in the literature. It has been applied to in-place welding of stainless steel tubing for the high-pressure hydraulic systems of the L-1011 jet transport which has 1500 welded joints. A T-ring for filler at the joint is used for welding 21-6-9 stainless steel tubing. Hughes Aircraft has used the orbital-arc tube welding process for space applications of aluminum tubing.

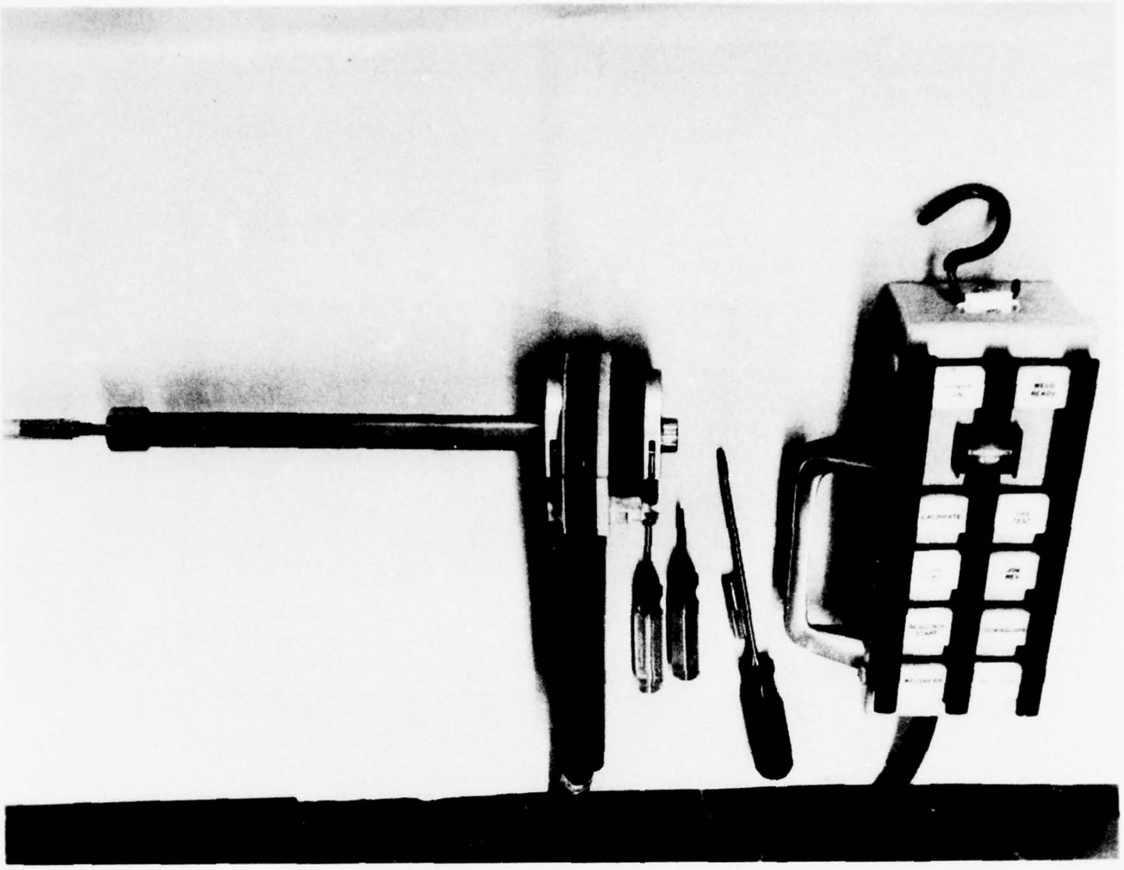


Fig. 25 Astro-Arc Weld Head With Offset Clamp for Nut and Mandrel Assembly and Accessories

Titanium tubing was considered in the past for a number of applications. Among these were the B-70 airplane, the Dyna-Soar and the Lunar Module. At that time, however, high-quality titanium alloy tubing was not available and equipment, particularly the welding head, was not perfected to the degree necessary for in-place space requirements and repeatability. In the late 1960's, however, Ti-3Al-2.5V alloy tubing of good quality became available and the necessary power supplies and welding heads came into being, and were marketed in the early 1970's.

The primary reason for choosing titanium tubing in aircraft hydraulic systems is its good strength-to-weight ratio. Titanium also has a low elastic modulus at room and elevated temperatures which results in a significant reduction (about 50%) in bending stress compared with steel at equal deflection. Its attractive corrosion resistance adds to its desirability, since corrosion coatings are not generally required below 550°F. Ti-6Al-4V alloy is generally not considered for production usage because of fabrication difficulties at the tube mills and excessive cost. Poor formability of this alloy also makes it difficult, if not impossible, to use it for bent lines commonly employed in aircraft hydraulic systems.

For the F-14A aircraft, bench-welding techniques were developed early in 1971 for joining appropriate Grumman-designed weldable Dynatube fittings to commercial 321 stainless steel and Ti-3Al-2.5V titanium alloy tubing using automatic tube welding systems (Fig. 26). Commercial tube welding machines were used to join prebent tubing having bend tangency distances less than one inch from the weld area (Fig. 27). This required reworking welding tools and fixtures so that F-14A lines could be welded without the necessity of re-routing lines. Fixtures were designed so that a threaded nut with an appropriate fitting could be mounted on one side of the welding gun. The weld centerline butt of tube and fitting falls directly beneath the tungsten electrode. The tube is placed in the other end of the gun with care being taken to insure that the tube is squarely seated in the fitting before the clamping device is closed. The machine is provided with a prepurge cycle so that the envelope around the joint to be welded can be filled with inert gas prior to arc ignition. The prepurge time can be set from one to 60 sec at any flow rate set on the flowmeter. Argon gas is usually employed to purge the weld head and backup.

Following parameter development (Fig. 28), welded specimens were fabricated for tests to meet F-14A requirements. All tests were performed to the following requirements and successfully completed with no failures occurring:

- Flexural Fatigue. This is a cantilever type of test at a combined stress of 25,500 psi (bending stress-14,700 psi and internal pressure - 3000 psi). Fittings are required to withstand a total of 10,000 cycles of flexure without leakage of fatigue failure

- Impulse. One cycle consists of a pressure impulse from 0 to 4500 psi, which is then dropped sharply to 3000 psi and held for a short time. Frequency is held at 70 ±2 cycles/min. It is required that fittings withstand 200,000 cycles without leakage or failure

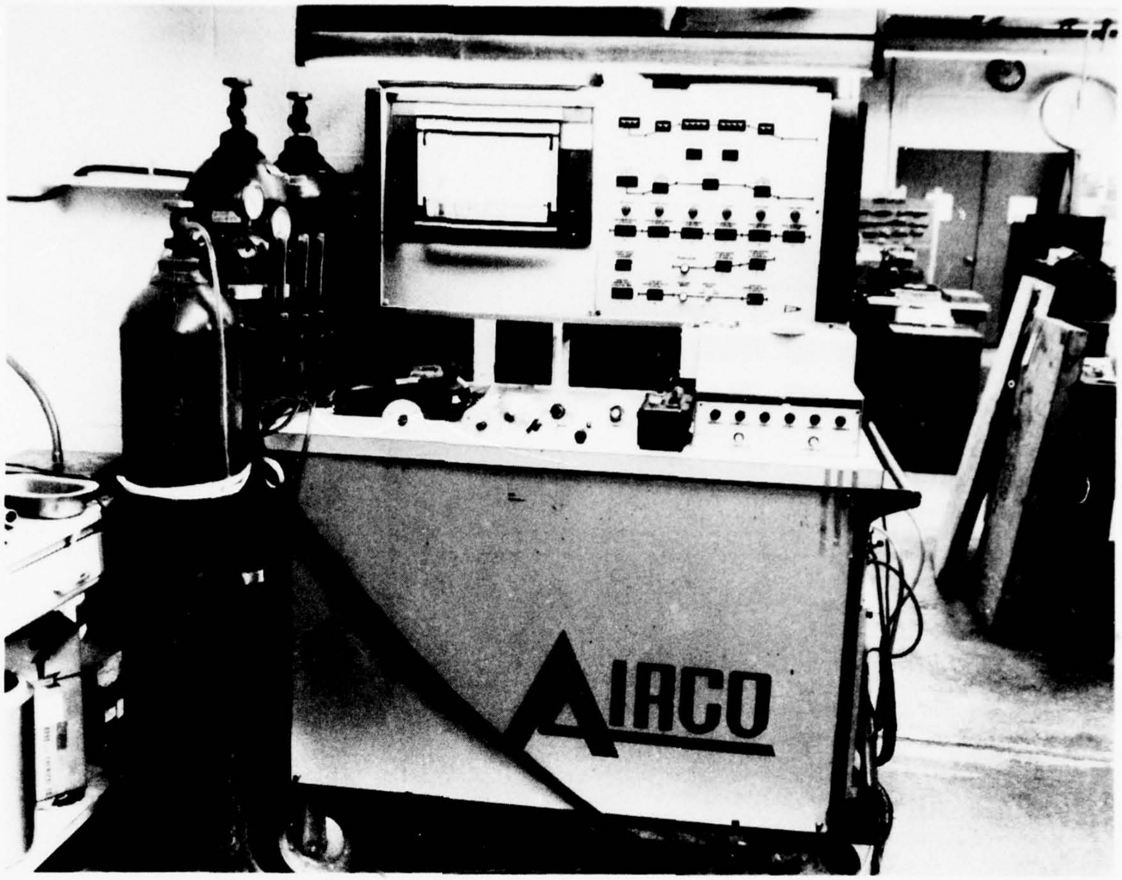


Fig. 26 Airco-Dimetrics Automatic Tube Welding System

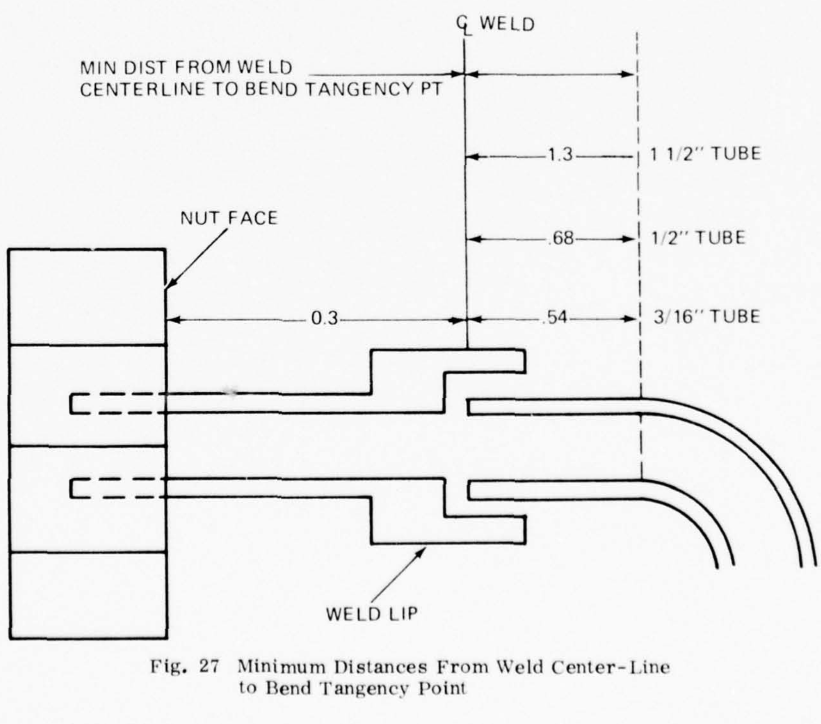


Fig. 27 Minimum Distances From Weld Center-Line to Bend Tangency Point

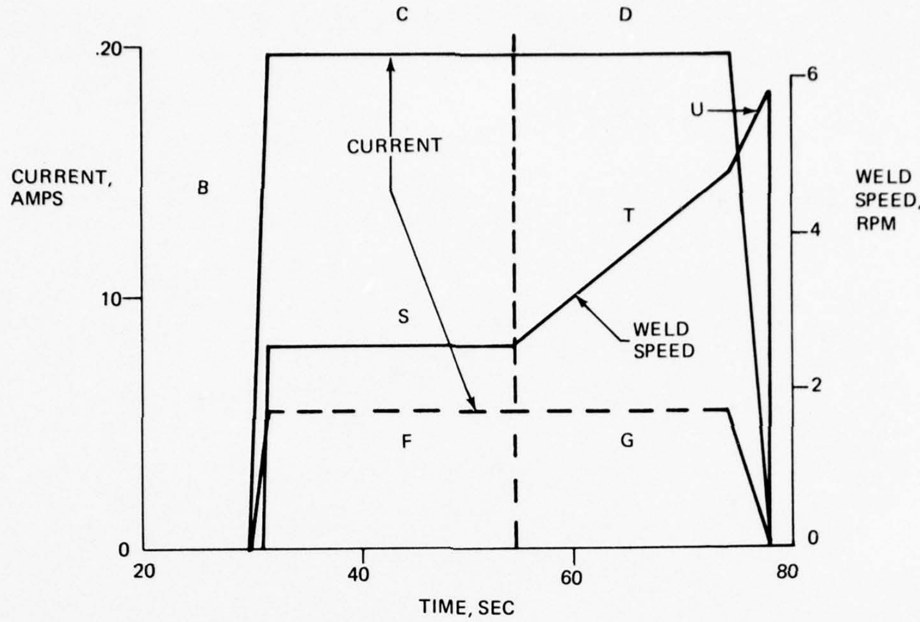


Fig. 28 Airco-Dimetrics Welding Schedule

- Burst and Leak. Tubes are first tested at a pressure of 6000 psi for 5 min. Pressure is then increased at a rate of 20,000 ± 5000 psi/min until burst or leakage occurs

- Repeated Assembly. One assembly cycle consists of tightening the fitting and breaking the connection twice, then retightening and proof testing at 6000 psi. This is done 25 cycles, after which the fitting is burst tested per the above burst and leak test requirements.

Several, one-in-diameter prebent titanium lines were then successfully joined at the ends of Dynatube fittings using a commercial tube welder to demonstrate the feasibility of welding production lines (Fig. 29). As a result of this effort, welding equipment was modified and tools were fabricated for production. After implementation of this process on the F-14A aircraft, hundreds of thousands of production welds have been made with less than 1% rejection. *All welds are 100% radiographically inspected.*

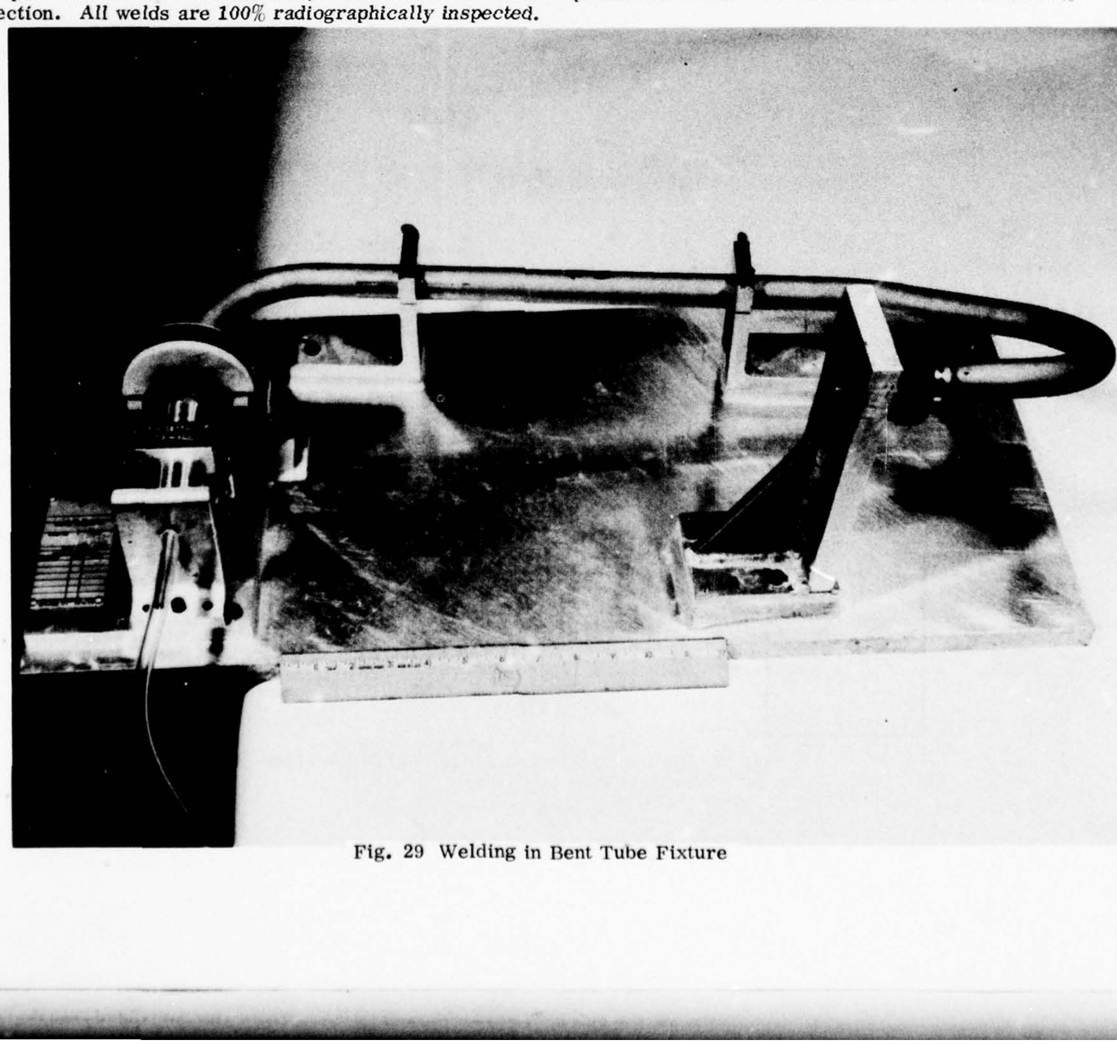


Fig. 29 Welding in Bent Tube Fixture

LASER WELDING AND CUTTING

The basic elements of a CO_2, continuous-wave (CW) laser system are given in Fig. 30. Lasers produce energy in the form of coherent light. In contrast to thermal light, coherent beams can be brought to a very sharp focus. Focused thermal light can burn wood, but focused coherent light evaporates steel, since specific energy levels exceeding one million watts per square inch can be obtained. This results in deep, narrow welds in many materials.

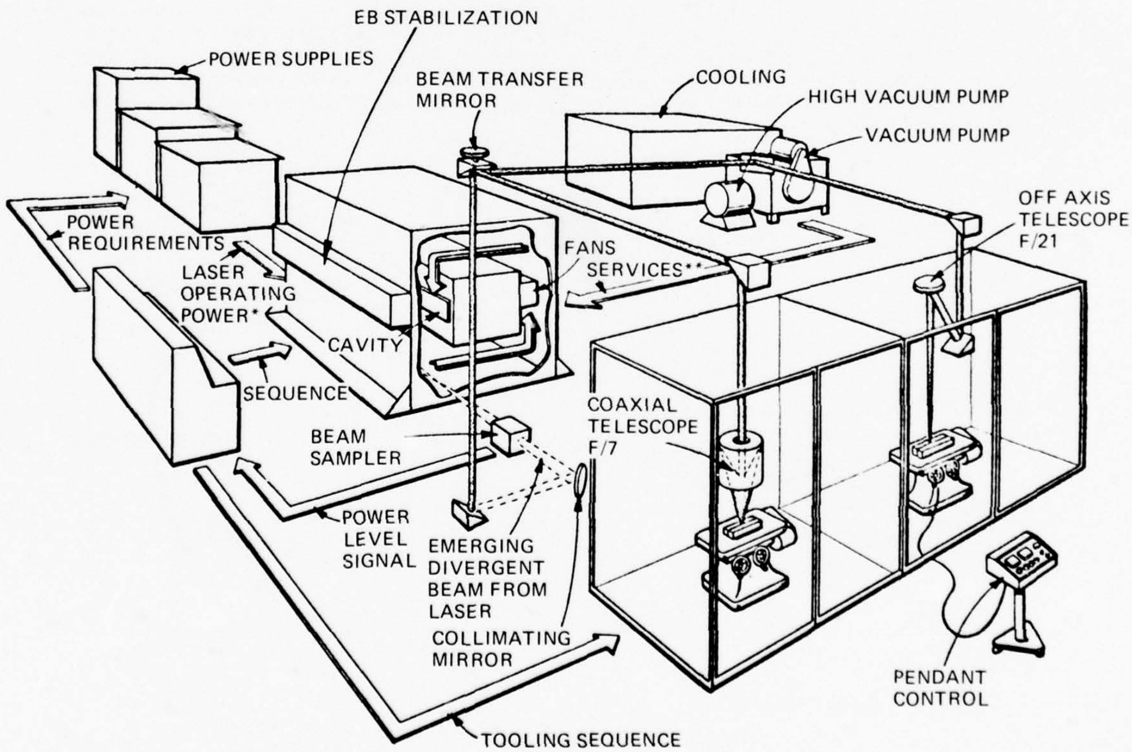
Although laser beam welding is not currently an accepted production welding process, it is discussed here because of the interest that has developed over recent years. Many people seem to be expecting more than this process can presently deliver; it is, therefore, important to determine the niche that laser welding can occupy in the near future. Since lasers can produce depth-to-width ratios similar to those for EB welds in materials around 1/4 in. thick, the process has often been considered as a potential competitor to EB welding. On the basis of more recent developments, however, it is more reasonable to consider it as a possible competitor to plasma-arc welding for materials up to 0.5 in. thick (this is near the thickness limit for 15-20 kw lasers).

Proposals to weld over 1/2-in.-thick metals by CW lasers seem to require multi-pass welds in joints with machined grooves. This adds to the cost and makes the process much less competitive with automatic arc welding and single-pass, straight-butt electron-beam welding. The tolerances and fit-up required for laser welding could be a major problem in this case. Certainly, it is possible to maintain control over fit-up requirements on straight butt versus vee-groove joints.

Laser power requirements also are very high for welding thick sections, since it has been found that lasers cannot be used effectively at slow welding speeds without loss of penetration capability. For example, laser welding requires around 80 kw. to penetrate two inches of steel at welding speeds around 50 in./min. For the same thickness, electron beam welding only uses around 15 kw at speeds as low as 5 to 10 in./min.

Another disappointment relative to airframe applications of laser welds has been the fact that fatigue properties in 1/4 to 1/2-in.-thick welds are reported equivalent to $K_T = 2$ or less (Ref. 6). It, therefore, appears that continuous-wave CO_2 laser welding will be directed mainly toward sheet gages where high-speed, low-distortion welds may result in better methods for wide-sheet structural elements.

Laser cutting has also been of considerable interest to the industry. We have found that for cutting metals 1/2-in. thick and greater, the laser cannot compete with plasma-arc cutting. For economically competing with chemical blanking and bandsawing when rough-trimming sheetmetal parts, we have successfully employed an NC-controlled 250-w laser as described in the motion picture film now to be shown (Ref. 7). We feel that approximately 1000-w lasers are the maximum-power units for cutting most sheet metal alloys economically except aluminum where 4-6 kw appears to be optimum at present.



*POWER FOR FANS, STABILIZATION AND DISCHARGE
**VACUUM (EB STABILIZATION AND CAVITY), MAKE UP GAS, AND COOLING (GAS AND MIRRORS) AND COOLING (GAS AND MIRRORS)

Fig. 30 Basic Elements of a CO_2 (CW) Laser System

DIFFUSION BONDING

Diffusion bonding (welding) is essentially a solid-state process in which metallurgical joints are produced by the application of pressure and heat for a predetermined time in a suitable environment that will not degrade quality or purity. Usually a vacuum has been employed, but joints also have been produced using inert gases.

Figure 31 shows schematically a production method developed by Rockwell International which is being employed to produce parts for the B-1 bomber and the space-shuttle (Ref. 8). Other methods of diffusion bonding can be classified generally by the type of equipment employed to apply the pressure. These include bar rolling mills, plate rolling mills, extrusion presses, hydraulic forging presses and resistance seam welding equipment using both spot and wheel electrodes.

The first major aerospace application of the process is on the B-1 bomber. Sixty-six Ti-6A1-4V alloy diffusion bonded parts were projected for use in each of the first three B-1 vehicles. These parts range in weight from about 40 lb to over 400 lb, with plan areas ranging from 180 to over 4000 in.^{2} The process has found application for producing parts which have deep pockets, complex configurations or heavy sections.

The press diffusion bonding process involves the assembly of premachined and cleaned titanium details in a tooling arrangement designed so that pressure can be applied to all interfaces being joined. This assembly is enclosed in a vacuum-tight stainless steel retort, which is sandwiched between ceramic heating platens and encased on the lateral surfaces with ceramic insulation. This assembly is heated to the processing temperature of 1700°F ±50°F. Pressure applied by a modified hydraulic press designed to apply pressure in orthogonal horizontal directions in addition to the vertical press loading direction. The interface joints bond by solid-state diffusion and deformation mechanism to merge the multiple pieces of titanium into a monolithic part. Additionally, the tooling can be configured so that local forging occurs under the applied pressure to form fillets. The resulting bond joint is observable macroscopically or microscopically only if sufficient variation exists between the microstructures joined to reveal the location of their interface.

Quality control procedures are maintained for diffusion bonded structures. For each type of configuration, a process verification part is fabricated and subjected to a thorough destructive test evaluation to demonstrate that the tooling and titanium detail designs, as well as the processing procedures, develop the structural configuration with properties required. On all parts, prolongations representative of the part are fabricated as an integral part of the as-bonded structure. These prolongations are evaluated by tensile test and metallographic evaluation. Additionally, bond interfaces are subjected to 100% ultrasonic inspection and are dye penetrant inspected after final machining.

It has been reported (Ref. 5 and 9) that using a combination of two patented processes - superplastic forming and diffusion bonding - three basic forms of hardware can be produced. In the first process, superplastic-formed sheet comes into contact with titanium details preplaced in a die cavity and becomes bonded to them, resulting in a reinforced-sheet structure. In the second form, two sheets are bonded together in selected discrete areas and in the same cycle; then they are expanded apart in the unbonded areas into a die cavity, resulting in an integrally stiffened structure. The stiffener is generally a hat section. In the third form, three sheets (two face sheets and a core sheet) can be selectively bonded and the face sheets expanded apart to fill a die, resulting in sandwich with an infinite variety of core patterns possible. These forms are initially being evaluated for production of a typical B-1 door. Preliminary projections indicate 50% cost and 31% weight savings over parts machined from titanium plate (Ref. 5).

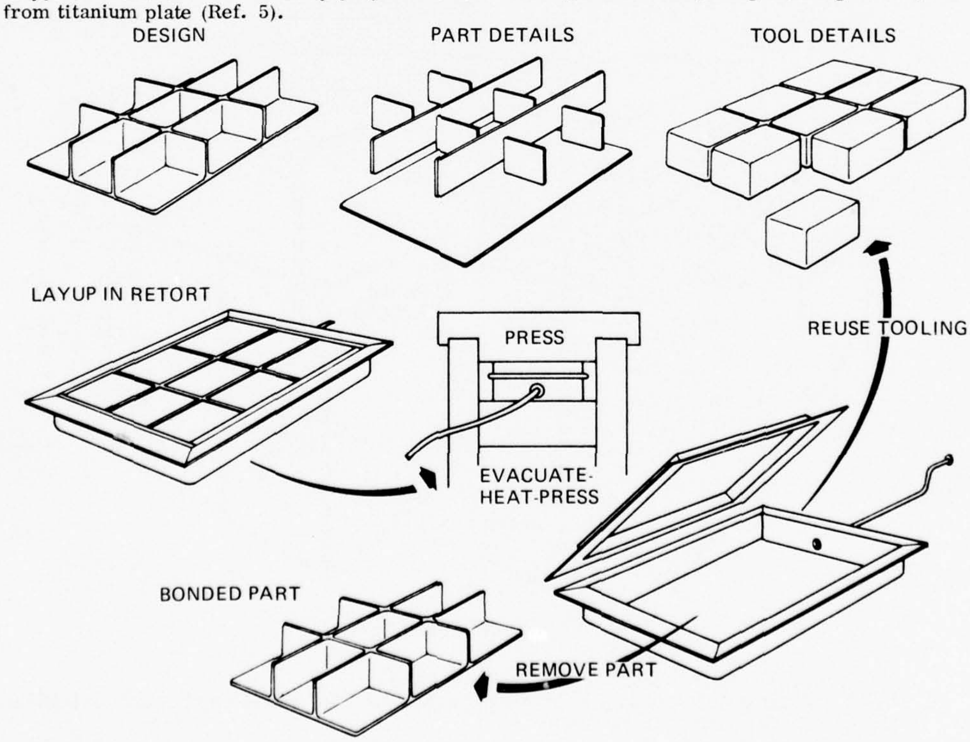


Fig. 31 Diffusion Bonding Process

OTHER PROCESSES

Other processes that have been evaluated for various applications are brazing, weld-bonding and weld-brazing. Aluminum parts have been fabricated primarily by weld-bonding. An aluminum weld-bonded fuselage component approximately 9 by 10 ft has been undergoing flight evaluations on a C-130 aircraft since November 1974 (Ref. 10). Manufacturing methods have also been developed for resistance spot-weld-ahdesive bond joining of titanium (Ref. 11). At the conclusion, a film will be shown that describes the process as developed at Grumman. The main limitation of the process for titanium is the temperature limit of the adhesive used.

The idea of substituting a braze alloy for the adhesive led to development of the process called weld-brazing (Ref. 12). During the development of the weld-brazing process, which combines resistance spot-welding and brazing, two primary approaches were investigated. One approach involved the use of pre-punched braze foil to facilitate spot-welding parent-metal to parent-metal and thereby eliminate interaction between the parent metal and the braze alloy. Another approach involved spot-welding of parent-metal to parent-metal using selected welding parameters and capillary flow of the braze alloy into the faying surface gap of the spot-welded joints. Both of the approaches were developed together and proved to be successful with each having particular advantages; however, because of its simplicity and potential low fabrication cost, the capillary flow approach was chosen for primary evaluation. Single-overlap and hat-stiffened compression specimens were fabricated using the capillary flow approach employing Ti-6Al-4V alloy sheet and 3003 aluminum braze alloy. Test results obtained indicated that weld-brazed specimens were superior in tensile shear, stress rupture, fatigue and resistance to buckling compared with joints fabricated by conventional means (Ref. 12). Initial results were obtained using vacuum brazing; however, similar results were also obtained from specimens brazed in an inert atmosphere (Ref. 13).

Following the in-house study, the process was evaluated by several aerospace companies and similar results have been obtained. The Boeing Company used weld-brazing in the fabrication of two titanium 737 spoilers under a Department of Transportation contract and reported that the process provided for lower tooling cost and resulted in a structure having improved mechanical properties. More recently, Lockheed-Advanced Development Projects (ADP) of the Lockheed-California Company has fabricated 10 weld-brazed 16x28-in skin stringer panels under a NASA contract which includes flight-testing on the YF-12 as well as ground-testing in a simulated supersonic aircraft environment. One of the panels has been installed on the YF-12 and has satisfactorily accumulated over 100 hr of flight service at speeds up to Mach 3. Ground tests of a weld-brazed panel which had been exposed to 1000 thermal cycles from -65°F to 600°F was equal in strength to an unexposed panel. Single-overlap tensile shear tests conducted by NASA Flight Research Center on specimens exposed for 5000 hrs at 800°F indicated no degradation as a result of exposure.

A cost study conducted by Lockheed-ADP indicated that the weld-brazed panels were approximately 20% lower in cost than the titanium integrally stiffened machined panel that they replaced. Based on these studies, weld-brazing promises to be a process capable of offering increased structural efficiency at a reduced cost compared to similar panels fabricated by more conventional techniques.

Aluminum-brazed titanium honeycomb sandwich structure was originally developed at Boeing (Ref. 14) for the SST and involved the brazing of titanium panels using 3003 aluminum filler metal. It was selected to withstand 450°F service temperature and to carry end loads up to 15,000 lb/in. Structural panels as large as 3x15-ft were successfully fabricated and evaluated.

The initial concern over use of the brazed system in aluminum corrosion environments was a latent galvanic corrosion problem created by the aluminum-titanium couple. Electrochemical, accelerated laboratory corrosion, salt spray and extensive field-service tests have confirmed the integrity of the panels. Also flight tests on 727 aircraft over a period of more than three years showed no detectable corrosion in exposed brazed fillet areas. The test panels were attached to the main landing gear and were exposed to varied weather and runway conditions depending on service routes of the airlines participating in the study.

The process was then proposed for other applications. One such was a structural redundant heavy section which could be used in high-load structural members such as landing gear beams, primary frames and flap tracks.

A recent program (Ref. 15) demonstrated the feasibility of this approach when a YC-14 engine support (Fig. 32) was selected and designed as a hybrid brazed titanium structure as a potential replacement for mechanically fastened, deep-pocketed machined forgings. Small frame forgings were EB welded together and subsequently brazed on either side of the honeycomb core blanket. Brazing was selected for joining webs to frames after evaluating a welded concept. The final outcome of the program indicated savings in machining, labor and materials costs from over 20 to 46%. Structural weight was also reduced over 40%.

INSPECTION AND DEFECTS

External and internal defects in titanium alloy weldments have a pronounced effect on their mechanical properties, especially fatigue resistance. An investigation was performed to produce typical defects encountered in gas-tungsten-arc, electron-beam, plasma-arc and gas-metal-arc welding processes by intentional variation of processing parameters and to evaluate fatigue endurance of defective weldments in tension-tension (= 0.1) fatigue (Ref. 16). Corresponding properties of the base-metal (Ti-6Al-4V, STOA condition) at various stress concentration (K_t) factors and flawless welds produced by conventional techniques were determined to serve as baseline data. Based on the results of this investigation and additional data contained in existing specifications, acceptance/rejection criteria proposed and representative weldments produced in the course of this program were evaluated in terms of the proposed standards (Fig. 33). Proposed acceptance criteria were indicated to be an efficient tool in detecting welds with inferior fatigue endurance.

Fatigue endurance of radiographically flawless weldments produced by EB, PAW, GTA and GMA processes did not vary significantly from corresponding properties of the base-metal. Except for cracks and EB welding bursts, typical defects encountered in production welding could be generated by variation of processing parameters. Cracks were detected only in GTA weldments produced under intentionally inadequate shielding. EB bursts could not be produced in welding blanks designed to simulate rapid cooling conditions existing after extinction of the beam and to change the shape of the molten puddle which occurs on transition from full to partial penetration.

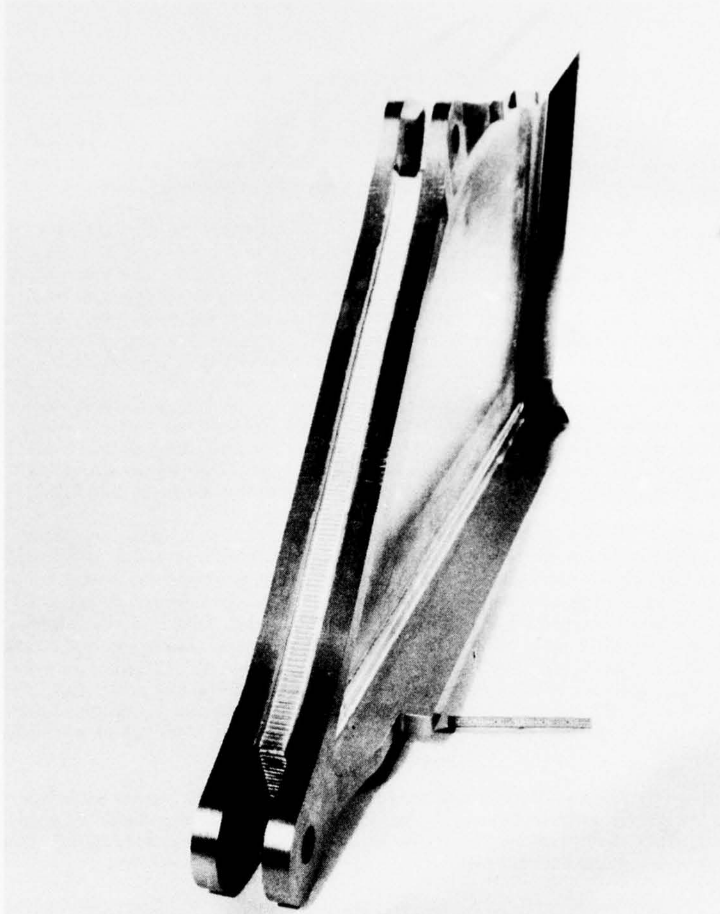


Fig. 32 Hybrid Brazed/EB Welded Titanium Structure

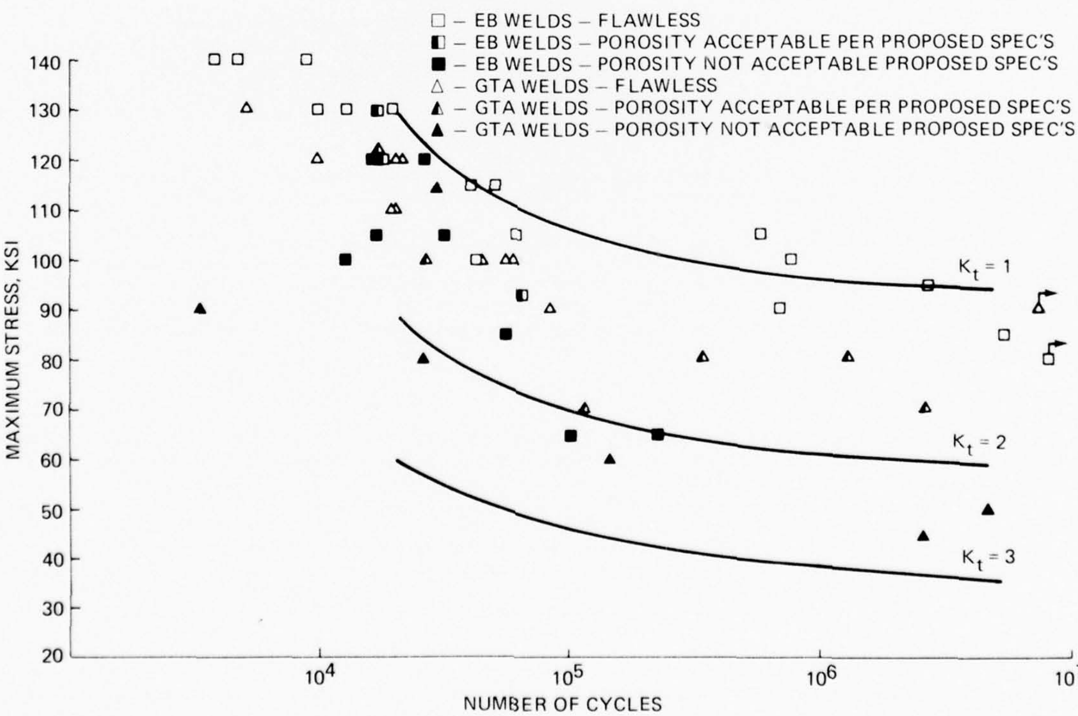


Fig. 33 Fatigue of EB and GTA Welds

All experimental weldments with (intentional) lack-of-penetration defects exhibited a drastic reduction in fatigue endurance. Low fatigue strength of welds with mismatched faying surfaces appeared to be caused by extensive changes in the weld contour rather than mismatch themselves. Blending of contours is required to improve fatigue strength of these weldments. The effects of shallow underfills and undercuts intensified with the thickness of weldments.

Drastic lowering of fatigue endurance was evident in burst-containing EB welds. In specimens containing intentional porosity and tested at high stress levels (100 ksi and above), no definite correlations were apparent between values of fatigue endurance and magnitude of defects. At lower stress levels, fatigue strength depends on the location of pores with respect to the surfaces of the specimen. Weldments with surface-connected pores had consistently lower fatigue endurance.

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Process and Metallurgical Factors in Joining Superalloys and Other High Service Temperature Materials

by

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SUMMARY

Aircraft gas turbines rely on materials which must operate durably at elevated temperatures. Fabrication methods to make turbine parts are selected for reliability and cost effectiveness. Thus nickel-base superalloys, which are the dominant heat resistant material used in aircraft gas turbines, are frequently metallurgically joined in manufacture or repair of a gas turbine. The nature of the superalloy class of materials makes joining difficult. Several problems exist in welding the superalloys such as heat affected zone hot cracking and post-weld heat treatment cracking. The nature of these difficulties will be described, including a metallurgical discussion of their causes. Methods for reducing or eliminating these problems will be discussed along with some general guidelines for joining this material class. Some examples of the processes and applications for joining will be reviewed along with descriptions of how processes are adapted to provide the quality, properties and reliability required for gas turbine use of welded superalloys.

INTRODUCTION

Manufacturing modern aircraft gas turbine engines offers a wide variety of challenging fabrication problems. This is in part due to the very high power density and low weight requirements of a modern gas turbine engine. A turbine has to develop as much as ten or fifteen horsepower for every pound that it weighs. Each excess pound that it weighs is a debit to the eventual performance of the aircraft that it propels. Operating economics depend upon efficiency and today, are increasingly important for both civil and military aircraft. Many contemporary factors require optimum efficiency such as the rising price of fuel and its impact aircraft operator cost. Engine performance is always required for both military and civil aircraft in order to provide the highest in aircraft performance. At the heart of both performance and efficiency is the ability to operate portions of the engine durably and reliably at very high temperatures. Absence of durability substantially increases maintenance cost. The dominant material that has led to the ability of the turbine to operate at high temperatures are the class of materials called superalloys. Although many materials are used in gas turbines such as titanium alloys, steels and in some cases aluminum and even plastic materials, one of the most extensively used material is superalloys. It is this class of materials that this paper will address itself to.

The other aspects of the major topic to be considered in this paper, of course, is joining or welding. One need only to examine a modern aircraft gas turbine to know that welding is extensively used to fabricate and repair many components in the powerplant including those made from superalloy materials. Welding is used as in any other manufacturing application to provide economical, reliable, lightweight forms of construction which are suitable for the requirements of the powerplant. Many welding methods are used to fabricate various segments or parts of the aircraft gas turbine engine. Although this paper will not attempt to document or give examples of all processes it is worth noting that gas tungsten arc, electron beam, resistance, plasma arc, and inertia welding along with brazing and diffusion bonding are all applied in various degrees to the joining of superalloys.

Superalloys are not an easy group of materials to fabricate. The very characteristics that provide them with their durability in an environment of high temperature, high stress and oxidation typical of the combustor or turbine portion of the engine, are the same characteristics which make them very difficult to fabricate and to weld. This paper will attempt to provide a broad introduction to superalloys and the problems and solutions to fabricating them. It will not contain extensive tabular "how to do it" information but shall try to explain the broad principles of the weldability and the approaches to joining superalloys. It will review the physical metallurgy of the materials, and several of the specific problems encountered with welding of superalloys such as hot cracking and post-weld heat treatment cracking. It will try to provide a general outlook on the requirement for thermal treatment of the superalloy before, during and after fabrication to improve weldability and ensure adequate properties and it will suggest some methods which have been used for specific problems in joining superalloys. Lastly, it will attempt to describe how processes have been adapted or developed to use with superalloys. Sufficient references will be included to permit the reader to search the open literature for further information.

The Metallurgy of Superalloys

Superalloys are a class of materials based on nickel and cobalt with large additions of other elements to achieve specific properties. Cobalt base alloys are used less extensively than nickel base alloys and in

a much more restricted sense. They do not have as broad a range of properties as the nickel base superalloys. Because they are somewhat less extensively used they will not be covered in this paper.

The widespread engineering use of nickel base alloys dates back to the 1940's when they were first introduced as heat resistant materials in gas turbine engines (1). Table I lists a select group of representative alloys and their introduction dates and compositions. These alloys started from a nickel-chromium base and possessed creep resistance and oxidation resistance which exceeded the then available stainless steel family. Solution strengthened nickel base superalloys have been used since that time with many specific alloys having been added. Today commercially available nickel base superalloys which are basically solution strengthened by addition of elements such as chromium, tungsten or molybdenum are used extensively for sheet fabrications. They also tend to contain carbon and other minor elements for control of workability and microstructure in general.

A major innovation occurred circa 1944 when titanium and aluminum were added to the basic nickel 20%-chromium solid solution strengthened superalloy to produce the precipitation hardenable superalloys. One early alloy, Inconel-X is shown in Table I. These additions produced the intermetallic compound which today is referred to as gamma prime (γ'). Gamma prime ($Ni_3(Al,Ti)$ order FCC phase) is the basic precipitate formed for most nickel base superalloys and has been used since the early days of precipitation hardened superalloys to achieve maximum strength for these materials (2). Today although aluminum is most commonly used to achieve a high degree of precipitation hardening, titanium, tantalum and columbium are used extensively in combination with it to achieve optimum properties for specific uses or applications. As the superalloys have evolved (Table I), higher levels of titanium and aluminum have been added to give more total hardening capability for additional strength at even higher temperatures. Other elements that are commonly added to the superalloys include molybdenum and tungsten for solid solution strengthening which remains an important factor for achieving the maximum desired properties. Another element found in a superalloy is cobalt which is added to adjust the γ' solvus and chromium which is added for oxidation/corrosion resistance (3).

Minor elements such as carbon, zirconium and boron are added to achieve specific grain boundary characteristics which contribute to the elevated temperature ductility, workability or other specific characteristics of the superalloys. Hafnium appears in recently developed superalloys, in particular case ones, to enhance hot ductility and castability which can be a problem in very high creep strength alloys (1). It is worthy to note, at this time, that Inconel 718 which is shown in the same table contains a large percentage of columbium. The benefit of columbium which was discovered and in approximately 1958 was found to produce a modified form of precipitate which has been more recently designated as gamma double prime (γ''). This alloy was conceived and developed primarily for fabricability and in particular for weldability. In subsequent sections, much more will be said about Inconel 718 and the role that columbium and other constituents of this alloy play in weldability.

A microstructure of a typical superalloy is shown in Figure 1. It is heat treated to produce the optimized microstructure for the maximum combination of creep strength, ductility etc. for this alloy. This particular alloy, Udimet 700 (See Table I) is a moderate strength superalloy used in both cast and wrought forms and it contains approximately 40 volume percent of γ'. It is worth noting in this photomicrograph

that 40% volume fraction of gamma prime produces a very dense array of precipitates. The basic background in this photomicrograph is a solid solution which consists of nickel, cobalt, chromium and molybdenum. The γ' precipitate exists as both large cubic blocks and as fine particles. Many advanced cast superalloys used today contain as much as 70 v/o of γ'. Therefore the hardening phase which is the one which is least ductile and the highest strength may be the majority phase in the alloy. Not shown very clearly in this micrograph but to be shown later are many of the grain boundary or minor phases which consist of carbides, borides, oxides and perhaps other compounds which will be shown later to produce many of the problems in the welding of superalloys.

Another factor which has been utilized to develop the maximum properties in this class of materials has been to process the materials to control microstructure (1). Today two of the most common forms of this approach are directionally solidified cast materials and more recently still the directionally solidified cast single crystal materials which contain no grain boundaries. These are shown in Figure 2 which shows cast forms of a typical superalloy article, a turbine blade, in 3 forms of controlled microstructure; equiaxed, directionally solidified and single crystal form. These casting techniques permit the use of very highly alloyed materials to optimize for strength and in some cases for oxidation resistance or corrosion resistance. These superalloys are particularly strong and ductile and can be used to temperatures to about 1800^{O}F. Although welding of these materials will not be a major part of this paper they will be discussed later in the paper to illustrate how joining relates to these materials.

Figure 3 shows that the increasing alloy content of the materials of Table I enables the use of materials at higher service temperatures. In this example, the 100 hour stress rupture life at a stress of 40,000 psi is used as a criteria and several of the alloys are compared at the maximum temperature to which they can be used. One can see in this particular micrograph that useful temperatures increase with the higher hardener content materials.

The very characteristics that lead to the high strength stable and oxidation resistance characteristics of these materials are the ones that which also lead to the problems that are encountered in fabricability. High temperature strength is frequently coupled with low ductility. The stability necessary for a material to exist in its high temperature environment for hundreds of hours without changing or degrading leads to other problems such as a very slow rate or very great difficulty in achieving stress relief. The inherent oxidation/corrosion resistance of these alloys derives from surface oxides which in turn lead to problems for example of the difficulty to wet these materials in a brazing or diffusion bonding operation. These factors are summarized in a simplistic but useful comparison in Table II.

If one takes the parameters of 1400^{O}F tensile strength and ductility (% elongation) and creates an index of fabricability by comparing the ratio of the ductility divided by strength, it is obvious that as an alloy becomes more heat resistant it has a much lower fabricability index. While there is no quantitative significance to this arbitrary index of fabricability it is helpful to illustrate that the higher strength, or heat resistant alloys do not have good fabricability. The problems that are found in welding these alloys can be broadly related to this index of fabricability.

In the remaining parts of this paper, I will be talking about several problems that effect the weldability of the materials. Specifically, I will be talking about hot cracking, about post-weld heat treatment

cracking and about the ability to produce welds with appropriate service mechanical properties.

Weldability Factors in Superalloys

There are three factors to be considered related to the welding of superalloys. Two of the three factors are problems and the third is related to the awareness to which all properly designed systems are subject; i.e. the overall concern for weldment properties. The two problems are hot cracking and the post-weld heat treatment cracking of this alloy class. Hot cracking is generic to all superalloys occuring to some degree with all fusion welding processes. Post-weld heat treatment cracking is not generic to all superalloys but most significantly affects the γ' hardened superalloys. It does however also occur to a lesser degree in severely restrained weldments made from superalloys hardened with γ'' (Ni_3Cb) even though this type of superalloy (Inconel 718 primarily) was specifically desgined to resist post-weld heat treatment cracking.

The properties of all superalloy weldments are of concern and require detailed consideration depending upon their application. Superalloys are obviously chosen because of specific properties, therefore the properties of the weldments made from them must also be intended to withstand the same environment. Each of these three factors; hot cracking problems, post-weld heat treatment cracking problems and properties of weldments will now be considered individually.

Hot Cracking

Figure 4 illustrates a hot crack in a superalloy weldment. It is very obvious from this photograph that the crack dominantly occurs in the weld heat affected zone (HAZ). Hot HAZ cracking occurs to varying degrees with different alloys depending upon the amount of restrain, the welding conditions and many other factors. Hot cracking is not a phenomenon which is unique to superalloys and the causes and the cures of hot cracking in superalloys are not generically different from those used to alleviate hot cracking in other materials. But in the specific there are some differences. Hot cracks can also be found in the weld metal of superalloys. However, weld metal cracks are generally resolved by use of good welding practices including proper design, proper choice of filler wire, and cleanliness. Therefore, most of the rest of this section will be intended to review the causes of and prevention of cracking in the heat-affected-zone.

As an introduction, a brief review of some of the thermal factors relating to welds will be shown in Figure 5. This shows the weld as a localized heating source which passes along plates being welded. In so doing the heat source causes a thermal wave with an abrupt front to pass through the material. Near the center, where the heat source is most intense, the metal is welded causing fusion of the abutting plates. Simultaneously zones adjacent to the fusion zone are also heated to very high peak temperatures at a very rapid rate and are then subject to cooling at a very rapid rate after they achieve peak temperature. Ahead of the curved line BC heating occurs, while behind it cooling occurs. If one were to examine the specific thermal cycles which occur along line AD as a function of distance from the weld centerline, the thermal cycles shown in Figure 6 would be found. As can be seen, the regions in the HAZ nearest to the fusion line experience peak temperatures approaching the fusion zone namely peak temperatures approaching $2400^{\circ}F$. These peak temperatures are reached in times of less than 2 seconds and cooling rates occur very rapidly following the achievement of peak temperatures. The affects of such rapid thermal

cycles on the materials are what cause microstructures of the HAZ to form as is seen in Figure 7. The events in the HAZ are examples of phenomena which occur in a very dynamic fashion usually of a non-equilibrium nature. Without excessively detailed explanation of the kinetics of phase reactions in the heat affected zone one can examine the metallurgical events which occur in the HAZ of one alloy. This example can be then projected into a reasonable model for what occurs in all superalloy materials and can serve as a rationalle for dealing with many of the problems in the superalloy HAZ's.

This figure shows what happens if one synthetically re-creates HAZ in Udimet Alloy 700, an alloy which was previously described and which is very difficult to weld. The micrographs shown here were constructed by simulating the HAZ using a well known device developed in the United States called the Gleeble (4). The Gleeble takes the thermal cycles just described in Figure 6 and imposes them on 1/4" diameter specimens of the alloy under consideration to simulate the metallurgical events and therefore microstructures which occur in the HAZ. In the HAZ shown here, peak temperatures as high as 1800^{O}F cause no noticeable changes to the HAZ microstructures. There is some dissolution of the γ' at 1900^{O}F peak temperature and this continues until 2100^{O}F which shows further dissolution of the coarse blocky γ'. Also visible in the 2100^{O}F peak temperature is a phase reaction beginning at a grain boundary. At 2125^{O}F this grain boundary reaction can be seen to proceed to a far more extensive state and is then readily identified as a local melting phenomena.

Notice in the background there is still substantial evidence of γ' in intragranular areas which remain hardened and tend to resist deformation. The presence of the incipient melting at the grain boundaries however is something that one can readily imagine could cause problems if the material were strained. Weld HAZ's are certainly strained by the heterogeneity of the thermal input and significant rigidity of the overall weldment. Thermal gradients moving at many inches per minute cause local plastic deformation to occur in the HAZ. This effect can be clearly illustrated by a photograph taken on a welded specimen in Waspaloy® (Figure 8). This illustration is achieved by taking a sample and electropolishing it prior to welding the specimen and then examining the surface of the HAZ after welding. As can be seen by the intensive slip banding that substantial amount of strain does occur in this area. Zones near the weld bead can be seen to be incipient cracks (arrows) in this HAZ due to the abrupt thermal cycling with the strain that is caused by this localized heating are the basic phenomena which cause HAZ cracking. This is a relatively simplistic treatment of the problem of heat affected zone cracking but it does show the affects which are actually observed and therefore are the basis for a reasonable model described for HAZ cracking (5).

A composite micrograph of the HAZ of a Udimet 700 weld with enlargement to show its detail can be used to accurately summarize the events that occur to cause HAZ cracking. Note that in this particular photo-micrograph the predominant amount of cracking that occurs happened in the region where there is a small amount of melting. This is the same kind of melting that was shown previously to occur predominantly in the area where only minor melting in the grain boundary or other very localized places occurs. This part of the HAZ is somewhat removed from the edge of the fusion zone and is where a low volume fraction of melting occurs. It is also where the localized strains that occur adjacent to the weld are greatest and can be forced to concentrate on the grain boundary areas. Here, grain boundaries with the presence of the wetting liquid cannot accomodate the strains and thereby separate, leading to cracking. It does not

usually occur where melting is more prevalent or where the HAZ does not melt. This part of a weldment has been identified as the partially melted part of the HAZ and must occur in all welds (5). In fact, the weld cracking problems that occur in other structural materials are frequently associated with localized HAZ melting of grain boundary regions containing inclusions or other minor phases (6,7). Sulfides and phosphides of steels and sometimes silicides in stainless steels are all often blamed for hot cracking phenomena which occur in these types of materials. One of the incidious aspects of the superalloys is that they are produced as a very highly purified material and the levels of impurity trace elements such as sulfur, phosphorous and others are kept at very low levels. In the example just shown, Udimet 700, in fact it has been found that the causes of grain boundary melting are frequently related to minor phases which form from the elements in the alloy used for improved hot workability (8). These phases are borides or carbides and therefore aggravate the problem of prevention of hot cracking in the weld HAZ because the alloying elements are important to the mechanical property and workability characteristics of the alloy.

In summary, therefore cracking is a difficult problem to resolve when welding superalloys. Hot cracking can occur in large scale which is visible to the eye or to conventional liquid penetrant inspection methods. However, even when weldments pass this normal inspection one can very often find very fine micro-cracks in the HAZ metallographically. Microcracks like this will be shown to be contributors to the next problem to be discussed in this paper, post-weld heat treatment cracking, and they may also contribute to property debits which will also be discussed in a later section. It is therefore difficult to produce a weldment totally free of any form of microcracking, in particular, in higher strength superalloys. Such conditions can be tolerated however and through the proper use of design criteria can they be rendered innocuous.

Hot cracking reduction and prevention methods however are not without value. Certainly by proper design of a weldment the total amount of restraint can be reduced substantially so as to reduce the incidence or intensity of cracking. Superalloys themselves must be and are made to very high quality standards in terms of purity and trace element controls as to reduce the incidents of cracking. In many instances and in many applications alloys are in some cases purchased to specifications which impose extra control of minor elements for the specific intention of weldment fabrication and the main interest are usually to prevent hot cracking problems. Further approaches to the reduction or elimination of hot cracking involved such factors as utilization of the proper filler wire. In welding very highly alloy materials sometimes the use of lesser alloy content filler wire alloys are used such as Hastelloy X, Inconel 625 or Inconel 62 filler wire. These are alloy filler wires which are relatively weak though ductile and may not meet full strength requirement. They can however be effectively used to reduce incidents of HAZ cracking. In the area of weld procedures, factors such as the use of the minimum amount of energy input is often effectively used to reduce hot cracking (10). For example, weld filler wire diameter is frequently reduced in order to permit the operator to weld with the minimum amount of weld current in order to achieve the appropriate amount of penetration or filleting for the structure involved. The reduced energy input reduces the volume of weld and HAZ material which undergoes shrinkage during welding thus reducing the strain to be accomo-dated during cool down and thus reducing cracking.

Superalloys are always welded in an inert atmosphere and the purity of the atmosphere is important to help reduce the incidents of hot cracking. Generally welding grade argon which contained less that 20 parts

per million total impurity content is used to gas-tungsten arc weld or plasma-arc weld the nickel base superalloys.

Post-Weld Heat Treatment Cracking

This phenomenon is a problem which occurs with virtually all superalloys. It has been called strain age cracking or delay cracking but most correctly is called post-weld heat treatment (PWHT) cracking. It is different from hot cracking and it is characterized by much larger cracks as seen in Figure 10. These cracks initiate most commonly in the HAZ but their crack length is much longer and they frequently extend through weld metal or for substantial distances in the parent metal itself. They occur during the heat treatment which is usually required to do one or both of the following: to re-establish the properties of the weldment itself as will be discussed in more detail later or to provide stress relief since superalloy weldments are prone to retain significant residual stresses.

Figure 11 illustrates schematically how PWHT occurs. During the welding of a material the peak temperature in the weld and HAZ result in very high residual stresses left at the time of the completion of the weld. When the part is placed in a furnace for post-welding treatment, two things begin to occur simultaneously. First, is that residual stresses begin to relax. Unfortunately for the superalloys the temperature range at which stress relief begins to occur is also the temperature range in which rapid precipitation of γ' phase occurs. The precipitation of γ' strengthens the material substantially while it is attempting to stress relief. The strengthening usually is accompanied by a reduction in the overall ductility. The combination of the inability of the part to stress relieve coupled with the fact that it is gaining in strength and losing ductility causes PWHT cracking. In general, the cracking tendency of superalloys for PWHT cracking is a strong function of the total amount of hardener content of the alloy itself.

Figure 12 is a plot which shows where most or many of the commercial alloys fit as plotted against their total hardener content. As the arrow shows those alloys with higher total Al + Ti content are more subject to PWHT cracking than those which are lower in hardener content. This correlation has been observed many times and appears to be related to the fact that the higher the hardener content the more rapid the age hardening response during PWHT and the lower ductility of the alloy all of which increase the tendency to cracking.

As was previously mentioned, PWHT cracking has a tendency to initiate in the same area of the HAZ which was prone to hot cracking. Figure 11 showed that the dominant crack in the patch test which is used for the detection of the propensity of PWHT cracking occurs adjacent to the fusion zone, i.e. the partially melted HAZ.

As shown earlier, one can duplicate the microstructures of the HAZ using the Gleeble and study their tendency to PWHT cracking. By doing so it has been shown that the onset of cracking in previous sound specimens tends to occur most easily in microstructures which have previously been synthesized to duplicate the partially melted HAZ in Waspaloy as shown in Figure 13 (12). A convenient curve to display the kinetics of PWHT cracking is the C-curve. The C-curve plots the incidents of cracking as a function of time and temperature and the further the C-curve is to the left the more easily a particular microstructure of material will crack. The C-curve shown in Figure 14 is for Waspaloy which was run in the Gleeble to represent both the partially melted HAZ (Heated to a temperature of 2225°F) and the adjacent part of the

HAZ (heated to just 2200°F) which has not quite locally melted. Although the HAZ microstructures are in other ways very similar, the fact that the extra 25°F produces partial melting causes a pronounced increase in its tendency to PWHT crack much sooner when undergoing creep relaxation from 70 KSI in the temperature range from 1200° to 1800°F (12).

This is an appropriate time to more extensively describe the effectiveness of the previously mentioned alloy, Inconel Alloy 718, as a deterent to PWHT cracking. This alloy is a material designed specifically to minimize PWHT cracking. If one examines C-curves which for both Waspaloy and Alloy 718 superimposed on the same axis as in Figure 15, the time, temperature requirements to cause cracking to occur in Alloy 718 are far translated to the right, which correlates well with general experience; i.e. the alloy is far less prone to PWHT cracking than Waspaloy (13). Alloy 718 utilizes columbium (Cb) as its primary strengthening alloying element. The micrographs in the next Figure 16 illustrate that the strengthening precipitate formed from Cb is of a different type than the strengthening precipitate formed from Ti or Al. γ' has been previously described as a face centered cubic precipitate based on the compound Ni_3Al. This precipitate called γ'' (gamma double prime) is based on Ni_3Cb which has the same stoichometry as Ni_3Al but it is a body center tetragonal precipitate. It forms much more slowly and appears to permit far greater stress relief prior to the hardening and lessening of ductility than γ' does (14). Because of its very much lower popensity to PWHT cracking, Alloy 718 is therefore used very extensively for applications not only in aircraft gas turbines but also wherever high temperature structural strength is required along with reasonable fabricability by welding because PWHT cracking can usually be avoided. Two cautions are to be noted here; Alloy 718 is not totally free from PWHT cracking although it does have a very much lower tendency. (When it's welded in heavy sections or in highly restrained configurations, PWHT cracking still can occur with Alloy 718). Secondly, Alloy 718 is still subject to hot HAZ cracking. Because of the excellent composition control and melt practice it is not excessively prone to hot cracking but it can be found to be hot short if good precautions are not exercised during its welding, if its compositions tolerances are allowed to deviate much from optimum and if its minor element content is permitted to increase (15).

Which use of Alloy 718 is a major approach to avoid PWHT cracking wherever possible it is not the only approach. It is often necessary to weld other superalloys which are more subject to PWHT cracking because their properties or specific characteristics are required for an application. In these cases there are things that can be done to reduce the incident of the particular weldment to PWHT cracking. By applying these methods it is possible to fabricate components by welding from the other more cracking prone alloys. Solution annealing a superalloy before welding can strongly reduce its tendency to PWHT cracking (16). Alloys such as Rene' 41 or Waspaloy would never be welded in the fully heat treated condition if possible because in that condition it would be most subject to PWHT cracking. The same material can also be rendered less subject to strain age cracking by controlling rate of heating during the post-weld heat treatment. Examining the "C"-curves in Figure 15 shows that by heating the part more rapidly it is possible to heat the material to a high temperature above which annealing or stress relieving can occur without intercepting the nose of the curve wherein cracking will occur. If this is done, it is possible to cause the residual stress to relax before the onset of γ' precipitation does occur. Under these conditions stress relief is fairly rapid, ductility is quite high and the part can be successfully heat treated after

welding without cracking. This is a feasible approach for certain structures where it is possible to rapidly heat it in a furnace or to have a structure which is not subject to excessive distortion due to non-uniform heating. Another approach which has been suggested for the reduction in the tendency toward PWHT cracking is the use of inert atmospheres or vacuum during the heat treatment after welding. This approach has been reported in some cases to reduce the tendency to strain age cracking (17). It has been postulated that this treatment excludes oxygen which accelerates the tendency for PWHT cracking to occur. Some evidence to the success of this approach has been demonstrated.

Another approach exists that has been used in certain superalloys which contain very high hardener to achieve successful welds and heat treatments without PWHT heat treatment cracking. This approach is found to be effective in the highly hardened alloys which are difficult to solution heat-treat and cool sufficiently rapidly so as to avoid all γ' precipitation on cooling from the solution heat treatment temperature. This is illustrated in Figure 17 which shows a group of micrographs in Waspaloy and Alloy 700. Waspaloy is a material which when cooled from the solution heat treatment temperature retains most of the Al in solution. In this condition, the micrograph shows no γ' and its yield strength is low and its ductility is quite high when compared with the same alloy in its fully heat treated condition. Alloy 700 shows that this result is not accomplished by solution heat treatment. For example, in the fully heat treated state of yield strength of 160 KSI and a ductility of 15% elongation is typical for this material. If one solution heat treats it and fast air cools it (which is its normal heat treatment) it has a 130 KSI yield strength and still only 25% elongation. In order to truly soften and ductilize the material a different kind of heat treatment is needed. This heat treatment is overaging. Overaging involves solution heat treat followed by heat treatment to form course γ' precipitate. For the optimum overage condition listed below the yield strength can be held to a low 80 KSI with an elongation of 40%, very similar in fact to that of solution heat treated Waspaloy. The optimum overaging heat treatment is 2100^{O}F for 4 hours, followed by a two-step overage at 1975^{O}F for 16 hours, followed by a slow cool down to 1850^{O}F for 4 hours, followed by an oil quench (18). This sequence of heat treatment steps permits maximum of gamma prime to precipitate in a relatively coarse fashion where it is least effective in strengthening. If the oil quench isn't possible it is almost as effective to overage and follow by a cool to room temperature which achieves a microstructure which will have a small amount of fine gamma prime. This increases the yield strength slightly and decreases the elongation slightly but not very drastically. The overaged and cooled microstructure material can be shown in a restrained welded specimen to have increased resistance to PWHT cracking. Figure 17 shows that solution heat treated Alloy 700 in a relatively low restrained weldment will crack severely in post weld heat treatment. If the same alloy is overaged and slow cooled prior to welding it achieves a substantial improvement in PWHT cracking resistance. While the illustration shows that the alloy is relatively prone to PWHT cracking, some applications which require the elevated temperature strength of Alloy 700 may be fabricated if the structure is not very restrained and is fairly thin gage.

In summary, PWHT cracking is a serious problem in welding superalloys. However, it can be reduced through several means. The first and foremost of which is to use Alloy 718, which has been developed to reduce PWHT cracking. There are, however, other approaches to reduce PWHT cracking involving variations in heat treatment of the material either prior to or after welding in order to reduce the incidents of cracking.

As will be shown later in some practical applications, the problem though it exists, can be dealt with in a reasonable fashion to permit the fabrication of some useful components by exercising the approaches described in this section.

Mechanical Properties of Weldments

This section will not present extensive documentation on the properties of superalloys and all the factors that affect them. However, it will describe the basic principles which are involved in maintaining adequate mechanical properties in superalloys which are welded. It is obvious that superalloys are heat treatable and that the heat treatments are a large part of obtaining and maintaining their properties. Thus when a weld is made in a superalloy, a heat treatment must be an integral part of the total processing of the component in order to optimize the properties as well as the physical integrity of the part to be made.

As an illustration, consider the data on Alloy 718 in Figure 19. The properties in the bar-graph identified as baseline are those of the strength and the ductility of the parent metal at 1100^{O}F (19). If a weld is made with the parent metal in the fully heat treated condition and transverse tensile properties are measured and shown in Figure 19 in the as-welded condition there is a very substantial loss in both strength and ductility. If the weld is made of parent metal in the solution heat treated condition and then the weldment is directly aged, substantial amount of the strength of the parent metal can be recovered. However, there is still a substantial debit in the ductility. This is true because some areas of the parent metal in the HAZ are partially aged or even overaged by the welding operation and post-weld aging alone does not fully recover the properties of the entire weldment. If however, the weld is made and then subsequently the entire part is fully heat treated, that is to say, re-solutioned plus aged, it can be seen that the properties of the welded structure are virtually equivalent to those of the parent metal. Some slight property debits are realized due to the presence of "cast" weld metal in the test specimen cross-section, However, in gas turbine usage, creep and fatigue properties are usually those of greatest concern for most applications and configurations. Several factors usually come into the total evaluation of the weldment when measured in fatigue as shown in Figure 20. The baseline properties for the alloy in this LCF test are unwelded sheet. One can see that the baseline is significantly higher than either of two configurations of the welded material. The weldments were tested with the weld reinforcement left on (bead on condition) or removed by a grinding operation to be flush with the surface of the parent metal (bead off condition). The welds, in 1100^{O}F LCF, are approximately 30% weaker than in the bead off condition. The presence of cast structure and HAZ is sufficient to produce this debit. However, if the bead is ground off the debit is reduced to less than 20%. Thus in the case of welded Alloy 718 (in LCF testing at 1100^{O}F) the presence of the weld reinforcement which only minimally effects tensile properties turns out to be an extra debit due to the stress concentration present at the location where the weld reinforcement blends into the base material. If the same welds were tested in creep, the properties of a weld with the reinforcement left on would probably be improved due to the additional reinforcement effect of the over-thickness.

So, there are several factors which must be considered. Certainly the sequencing of the welding and heat treatment must be planned to obtain the maximum properties in the weldment. The choice of filler can also influence specific properties even though this has not been shown. This can be relatively less

important in applicants where full parent metal properties are not required due to the configuration of a weld, the location of the weld or the service requirements of the weldment. It is not uncommon to have welds designed with the joints region thicker to reduce the stresses at the weld to achieve a practical, usable welded structure. It is also worth re-emphasizing that for many welds particular properties can vary as has been shown. Therefore, the design and fabrication of a welded superalloy must utilize those properties which are critical to its application.

To try to illustrate the property variance as a function of all weld or configuration parameters would be a prohibitive task and it will not be done. The critical caution is that when a weld is designed and fabricated all factors must be considered so that the entire system can be evaluated; fabricability, properties, repairability, distortion and certainly cost.

Applications of Joined Superalloys

Many welded superalloy components have been used in aircraft gas turbines. Most welds are made with conventional welding processes such as gas tungsten arc or plasma arc as has been previously described. The most common applications have been for use in static structures, that is non-rotating components. A good example of a large complex fabricated weldment is shown in the Figure 21. This component is an Alloy 718 diffuser case for a large commercial transport engine. This diffuser case guides the gas flow from the exit of the compressor and into the combustion area. A component like this weighs several hundred pounds and contains hundreds of inches of both plasma arc and gas tungsten arc welds. Most of the welds are made automatically, i.e. with machine welding rather than with manual operators. Large circumferential or axial welds are usually easier and more reproducible to set up using machine welding. Plasma arc welding is becoming increasingly used because it is easier to control in terms of under bead contour. It is also usually a lower energy input process which results in fewer cracking problems. Many of the welds made on such an assembly must be made manually because it is more economical to make complex contour welds or out of position welds by hand. The filler wire for this case would be Alloy 718. This case would be welded in the solution heat treated condition and after it is inspected and found to be free of defects, it would then be entirely re-solutioned and aged prior to final machining. Thus any minor distortion which is realized during the final heat treatment can be accomodated during final machining. Generally heat treatment cycles are controlled to be as slow as possible for such large structures so as to minimize distortion. Cases like this may occasionally be made and contain some defects. Cases are inspected with both radiography and with liquid penetrant inspection in order to find possible defects and wherever necessary repair welds can be made prior to the final heat treatment and machining. A case can occasionally develop distress after it goes into service and may contain small cracks. One of the benefits of using Alloy 718 is that it is readily weld repairable. Procedures have been devised and instituted for repair in the field as required. An example of a type of small defect near a boss weld which has been found to occur is shown in Figure 22. These are able to be ground out and weld repaired. Such repairs are easily accomplished and have been applied successfully. After welding the area must be locally heat treated as shown in Figure 22 to achieve proper restoration of properties and to reduce residual stresses in the area caused by the repair weld. In this illustration electric resistance heated blanket is applied and held in place with appropriate insulation and the stress relieving temperature 1325^{O}F can be applied for the proper duration for that specific component and repair procedure.

Welding is also conducted on both blades and vanes for both new parts and for weld repair. Due to the complexity of turbine blades and vanes, massive structural welding is not usually accomplished because it is difficult to achieve the defect free welds necessary for utilization and service and to obtain full mechanical properties in blade and vane alloys However, parts for use in gas turbine are costly and when minor cracks or minor service distress occurs after long service operation it is often desirable to weld repair and refurbish the part rather than to replace it. One example of this is shown in Figure 23 which shows the sequence of weld repair for turbine vanes. In this particular example the turbine vanes shown are of a cobalt base alloy, however some nickel base vanes are also repaired in a similar manner. If there is a crack which is found during a normal inspection interval for an engine (by liquid penetrant or visual inspection) it is reasonable to grind out the defect and to weld repair using filler wire such as Inconel Alloy 625. A similar repair is shown in Figure 24 on a turbine blade wherein its tip is worn due to normal service exposure. A weld build-up procedure exists which can restore a blade of this type to normal use for many hours of additional service time. It is very common to provide weld repair procedures for operators of aircraft gas turbine because it is a very important element in the overall maintenance of such an engine.

Due to the difficulties in welding the superalloys, processes are adapted or introduced which have certain specific characteristics. Such is the case for a process which will next be described. In the joining of many shapes that go into aircraft gas turbines large cross-sectional areas and complex contours are used. These factors may make conventional welding impossible due to the problems previously discussed and compounded by requirements to join large areas. Much research and development has gone into seeking to apply other processes such as diffusion welding and brazing to superalloys for structural application. Each of these processes have their disadvantages. Braze joints are typified by limited ductility and cannot be used to extremely high temperatures because of their tendency to remelt if overheated or to be relatively weak at the service temperature of a part. Diffusion welding of superalloys has been found to be difficult due to the surface oxides and intermetallic compounds which tend to form on the surface which is due to their very nature as oxidation and corrosion resistant materials. A process has been developed however at Pratt & Whitney Aircraft which combined the manufacturing ease of brazing and with the quality of joints which is considered typical of diffusion welding. This process is called TLP® bonding (20,21). TLP stands for Transient Liquid Phase and it is a diffusion bonding process which utilizes the ability of a designed interlayer composition to melt and subsequently resolidify to accomplish the bond. Schematic illustration of the process is shown in Figure 25. An interlayer material in thin foil form is placed between the two components to be joined. When the entire assembly is heated to a given temperature the bonding temperature, the interlayer, melts because of its composition. The part is then held at this same temperature at which through diffusional processes the bond region is caused to resolidify and homogenize through the changing composition in this area. By suitable choice of interlayers of bonding parameters and design of the part it is possible to produce homogeneous bonds as shown in the micrograph which are impossible to discern both chemically and mechanically. For example, some mechanical properties are shown in Figure 26 for TLP bonds made in MAR-M200 alloy. In both low cycle fatigue and in stress rupture at very high temperature (1700 and 1800°F respectively) it is possible to produce bonds which exhibit parent metal properties. Other properties if measured would be also equivalent to the parent metal such as high cycle fatigue, tensile or shear properties. The theoretical model or TLP bonding is

illustrated in Figure 27 in the form of a hypothetical binary phase diagram. The base alloy to be bonded and the interlayer are shown in the illustration on the pseudo-binary diagram. When the assembly is heated to the bonding temperature, which is pre-selected based on the interlayer composition and the parent metal to be joined, the interlayer melts. When the assembly is held at the bonding temperature the diffusing species move in the direction to create homogeneity. Since the interlayer is thin (usually <.003" thick) the melting point suppressant in the interlayer alloy tends to diffuse and becomes dissolved in the parent metal. As a function of time, the average composition of the joint region tends to travel across the temperature tieline for the bonding conditions chosen. Once the assembly has been held at bonding temperature for sufficient length of time the composition shifts toward and intercepts the solidus near the parent metal. In so doing the joint isothermally solidifies. Further diffusional heat treatment drives the composition to be superimposed on that of the parent metal. This is possible because a large dilution effect is possible due to the relative mass of the part compared with the interlayer. Thus by controlling metallurgical process variables of the interlayer composition and the process time, by providing appropriate interface match-ups by tooling and mating surface preparation, and by maintaining the cleanliness it is possible to achieve excellent bonds in very easy fashion.

An example of a production application for this process is shown in Figure 28 which shows TLP bonded low turbine vane clusters currently produced for an commercial turbine engine. Individual vanes are assembled and the entire manufacturing cycle concludes as shown in Figure 29 with a very large number of these components assembled into a conventional vacuum furnace. The process is conducted in vacuum (generally 10^{-4} torr) to avoid any contamination problems while the parts are in the furnace. A typical furnace run is 4 to 6 hours and in the case shown here several hundred parts can be done simultaneously. Current production data for this component which has now exceeded 100,000 parts, has shown that the yield of acceptable parts has been 99.7%, i.e. of every 1,000 parts bonded 997 are acceptable for engine use. TLP bonding in addition to being applied in currently shown production application is suitable for other advanced applications and is being evaluated for such applications. The TLP bonding process can be applied to a very wide spectrum of superalloys including ones with controlled microstructures which were introduced in the early part of this talk. For example joints can be made in direc[illegible]y solidified alloys, powder metallurgy alloys and even in single crystals. It is also possible to ma[illegible] them into similar alloy combinations by appropriate design of bonding parameters and interlayers. While process is fairly new it is hoped that it will be applicable to a larger number of applications in the near future.

CONCLUSIONS

In conclusion, the superalloys due to their very characteristics are very difficult to fabricate. They have been shown to be subject to hot cracking, PWHT cracking and they have shown to have sensitive mechanical properties when welded. But the difficulties are not insurmountable. Work done to date has shown that welded parts can be made successfully by attention to details and by alert consideration of the entire system. To do the job correctly one needs to design parts correctly, choose the materials correctly, select the right process, properly sequence operations prior to and after the welding operation, understand both the problems and the factors which can be used to solve these problems in an intellegent fashion. Processes are adaptable to the joining of superalloys and some processes have been developed for the purpose of joining superalloys. The state-of-the-art is not perfect and that better application of superalloys in

welded form is still possible. More work is needed in order to expand our ability to fabricate these materials. New weldable alloys could be developed as well as improved filler wires for their welding. The basic purity of material could be controlled better to aid in the resistance of hot cracking of the alloys to be joined. We need to understand more about the appropriate heat treatments including the nature of the atmospheres, heating rates, proper temperatures, etc. to provide the optimum results in the structures to be made. Process factors such as proper choice of the welding process, the filler wire, the welding parameters which are chosen and even the operator technique can all contribute significantly to the successful joining of the superalloys. One must always maintain in mind the total system, the part, the design, the heat treatment, etc. Only by considering the entire system can you deal with the successful fabrication of parts by these materials and processes. However, there is still more that could be learned and further research it is hoped will be able to still further improve our understanding and knowledge about these various factors. Hopefully it will enable us to do more with the application and fabrication of superalloys for uses not only in aircraft gas turbine but wherever high temperature, corrosion resistant materials are required.

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TABLE I

COMPOSITION AND CHRONOLOGY OF NICKEL BASE SUPERALLOYS

ALLOY	DATE	C	Cr	Co	W	Mo	Al	Ti	OTHERS
INCONEL	PRE-1940	.1	15	--	--	--	--	--	Fe-7
INCONEL X-750	1944	.04	16	—	—		0.6	2.5	Fe-7 Cb-1
HASTELLOY X	--	.1	22	1.5	.6	9	—	18.5 Fe	
WASPALOY	1951	.07	19	14	—	3	1.3	3.0	.1 Zr
UDIMET 700	1953	.10	15	19	—	5.2	4.3	3.5	.02 B
INCONEL 718	1958	.05	18	—	—	3	0.6	0.9	Fe-18 Cb-5
AF2-1DA	1966	.15	12	10	6	3	4.6	3.0	Ta-1.5 Hf-1.5
MAR-M200	1970	.15	9	10	12	—	5.0	2.0	Cb-1 Hf-2

NOTE: Alloy Compositions taken from MDC1C-73-14 Report, June 1973

TABLE II

RELATIVE FABRICABILITY OF SUPERALLOYS BASED ON PROPERTIES AT 1400°F

ALLOY	STRENGTH UTS	DUCTILITY %EL	FABRICABILITY INDEX %EL/UTS
INCONEL	27	46	1.7
WASPALOY	115	28	0.24
UDIMET 700	150	30	0.20
MAR-M200	135	3	0.02

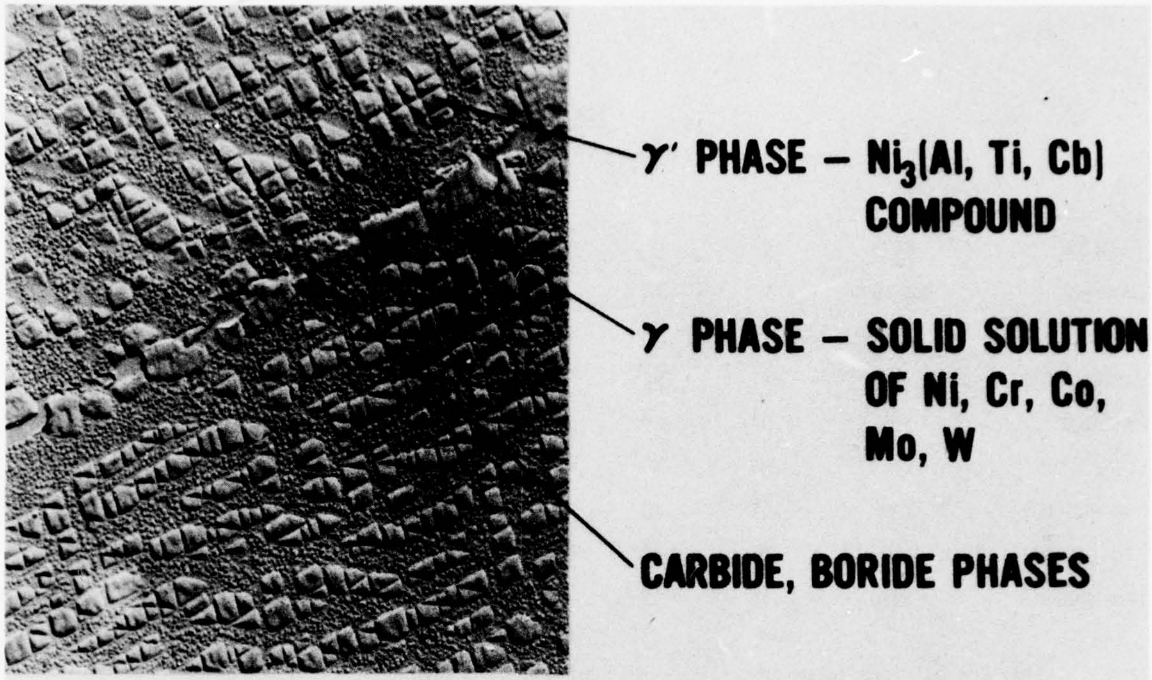

FIGURE 1: MICROSTRUCTURE OF ALLOY 700 IN THE FULLY HEAT TREATED CONDITION, I.E. 2140°F/4 HOURS PLUS 1975°F/4 HOURS PLUS 1550°F/4 HOURS PLUS 1400°F/16 HOURS.

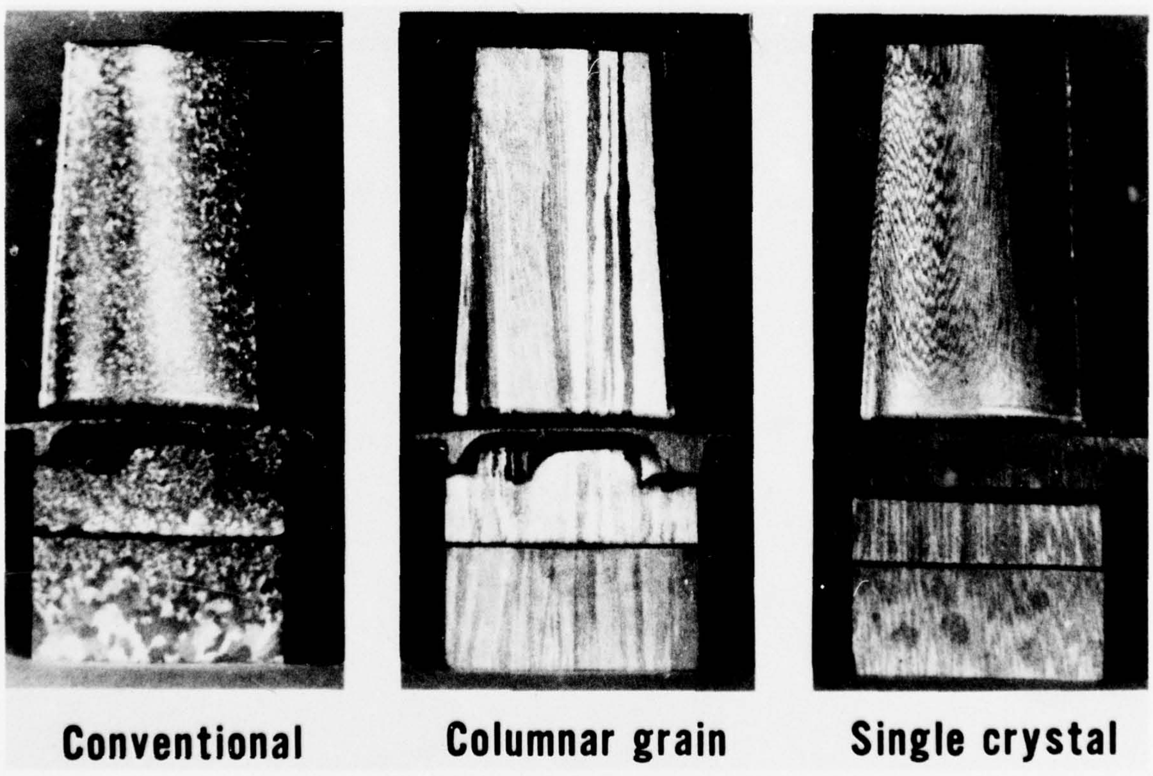

FIGURE 2: CAST TURBINE BLADES IN CONVENTIONAL EQUIAXED, COLUMNAR AND SINGLE CRYSTAL MICROSTRUCTURE, ALL MAR-M200 + 2 Hf COMPOSITION.

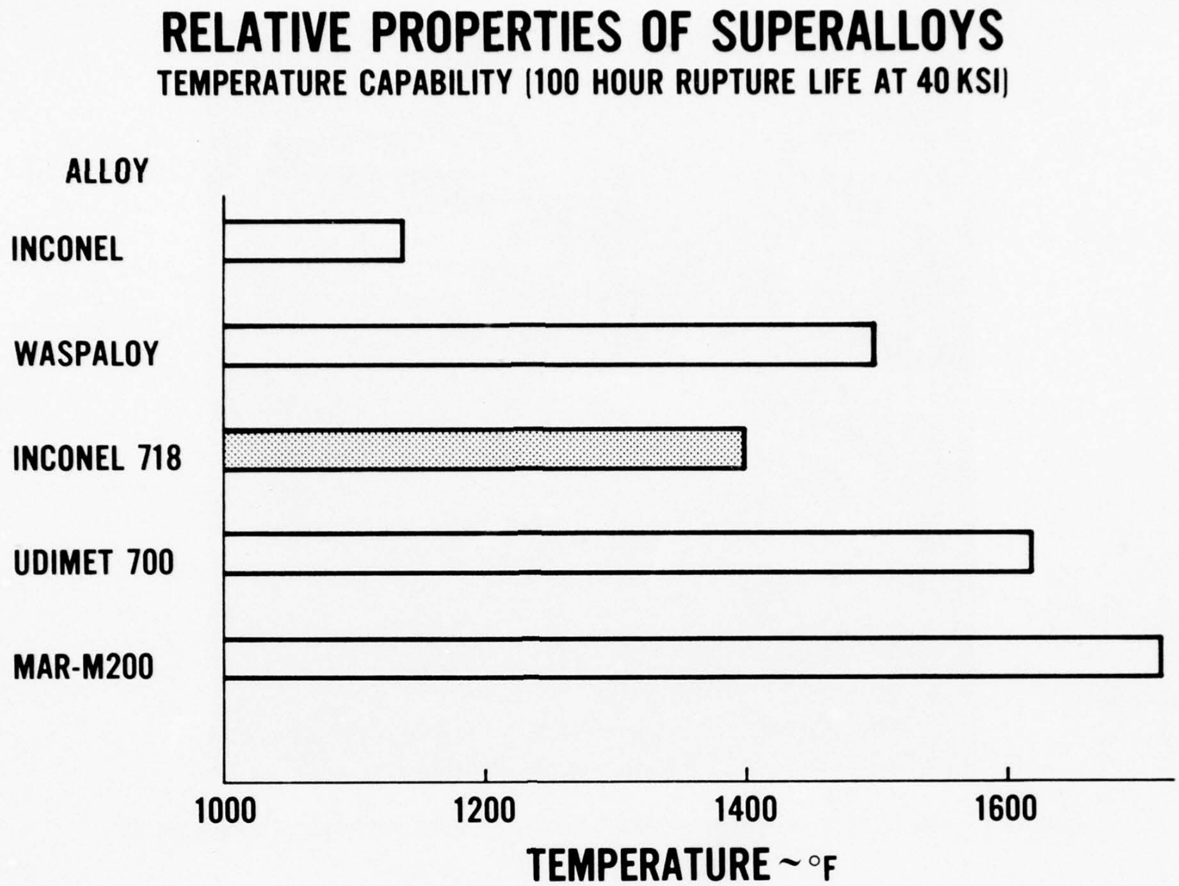

FIGURE 3: MAXIMUM SERVICE TEMPERATURE OF SEVERAL SUPERALLOYS BASED UPON 40 KSI, 100 HOUR RUPTURE LIFE REQUIREMENT.

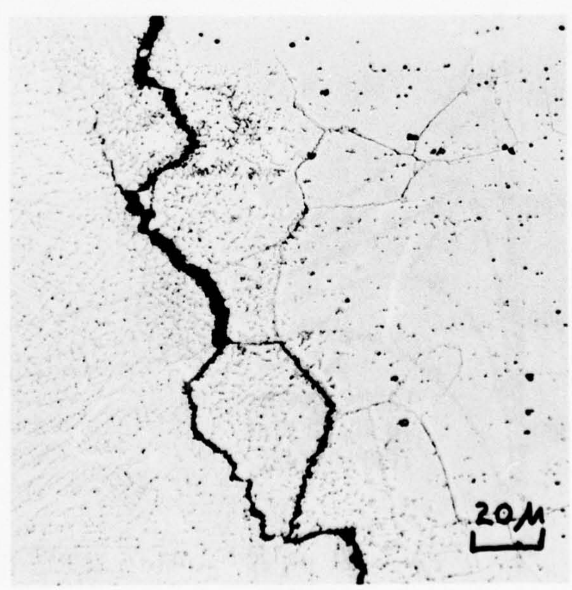

FIGURE 4: HOT HAZ CRACK IN ALLOY 700 AFTER GAS-TUNGSTEN ARC WELDING.

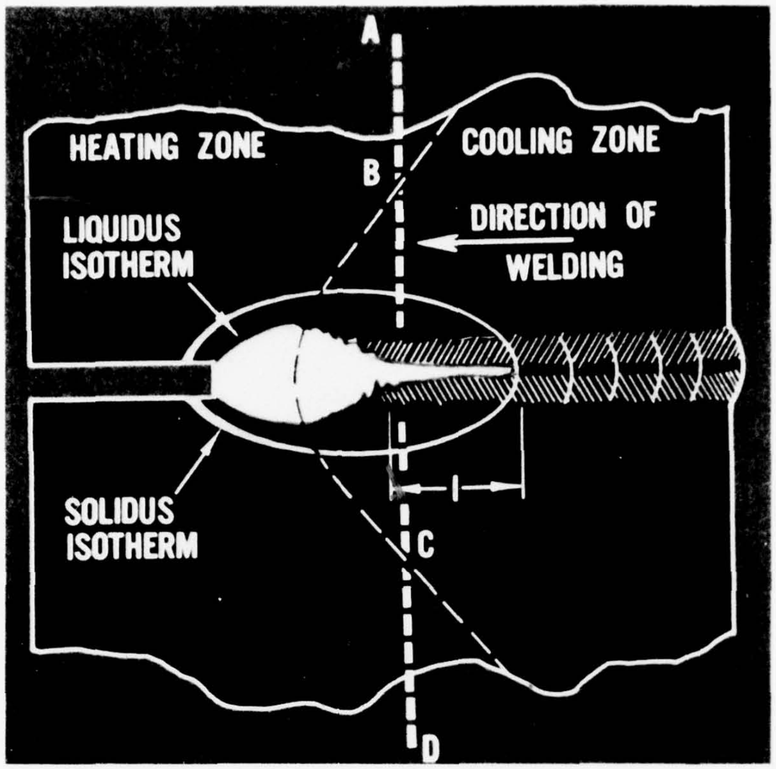

FIGURE 5: SCHEMATIC DIAGRAM OF THE THERMAL CONDITIONS WHICH OCCUR DURING FUSION WELDING.

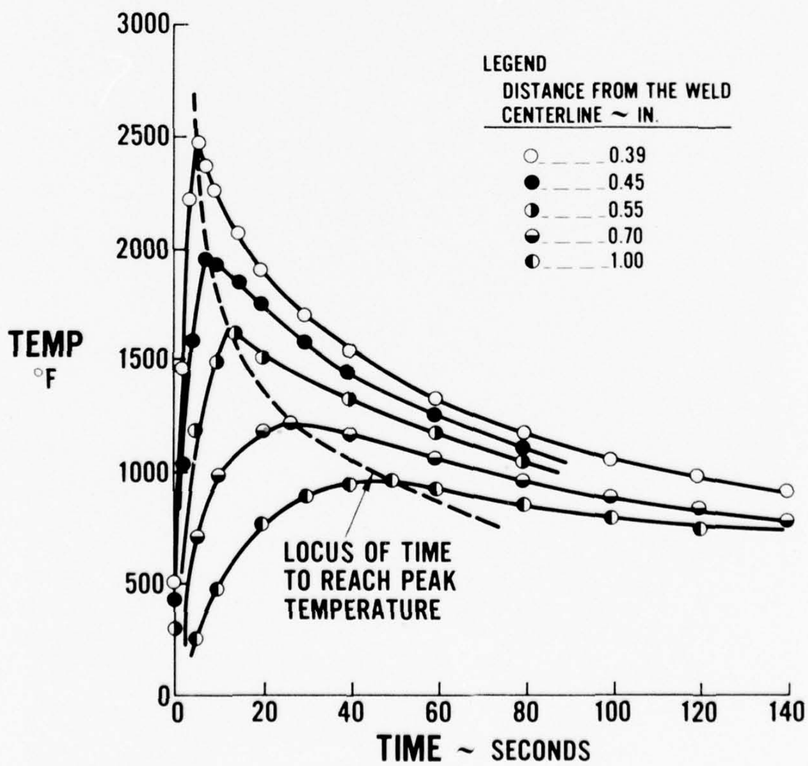

FIGURE 6: THERMAL CYLES ALONG LINE A-D IN FIGURE 5 AS A FUNCTION OF DISTANCE FROM THE WELD CENTERLINE. DATA FROM 1/2" THICK STEEL PLATE BUT CURVES PREDICTED TO BE EQUIVALENT FOR 1/16" THICK SUPERALLOY.

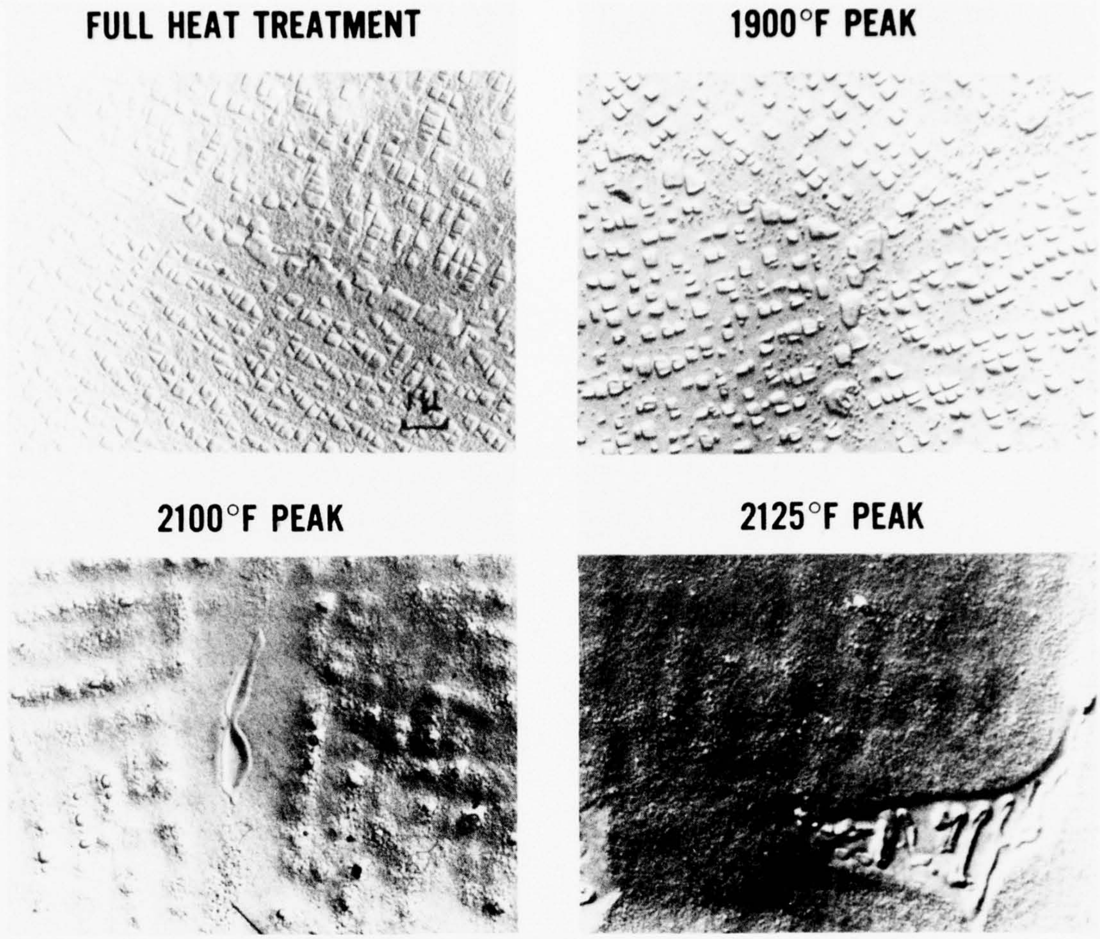

FIGURE 7: MICROSTRUCTURES PRODUCED IN ALLOY 700 TO SIMULATE PORTIONS OF THE HEAT AFFECTED ZONE CORRESPONDING TO THE PEAK TEMPERATURE SHOWN.

FIGURE 8: STRAIN IN HEAT AFFECTED ZONE IN WASPALOY WELDMENT IN 0.060" THICK SHEET. SPECIMEN ELECTRO-POLISHED PRIOR TO WELD.

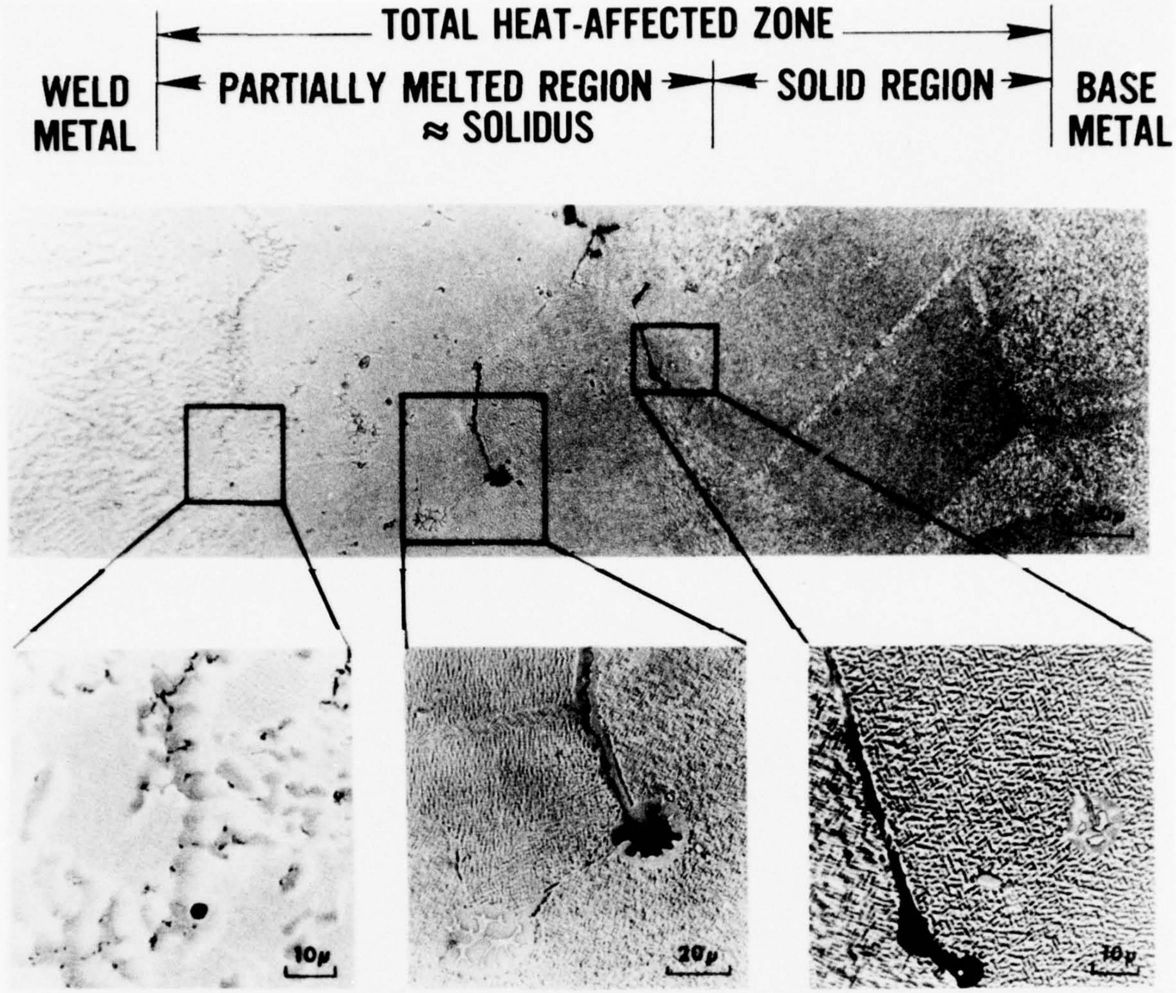

FIGURE 9: METALLURGICAL MODEL FOR HEAT AFFECTED ZONE CRACKING IN SUPERALLOYS.

FIGURE 10: EXAMPLE OF PWHT CRACKING IN A WASPALOY RESTRAINED PATCH TEST SPECIMEN.

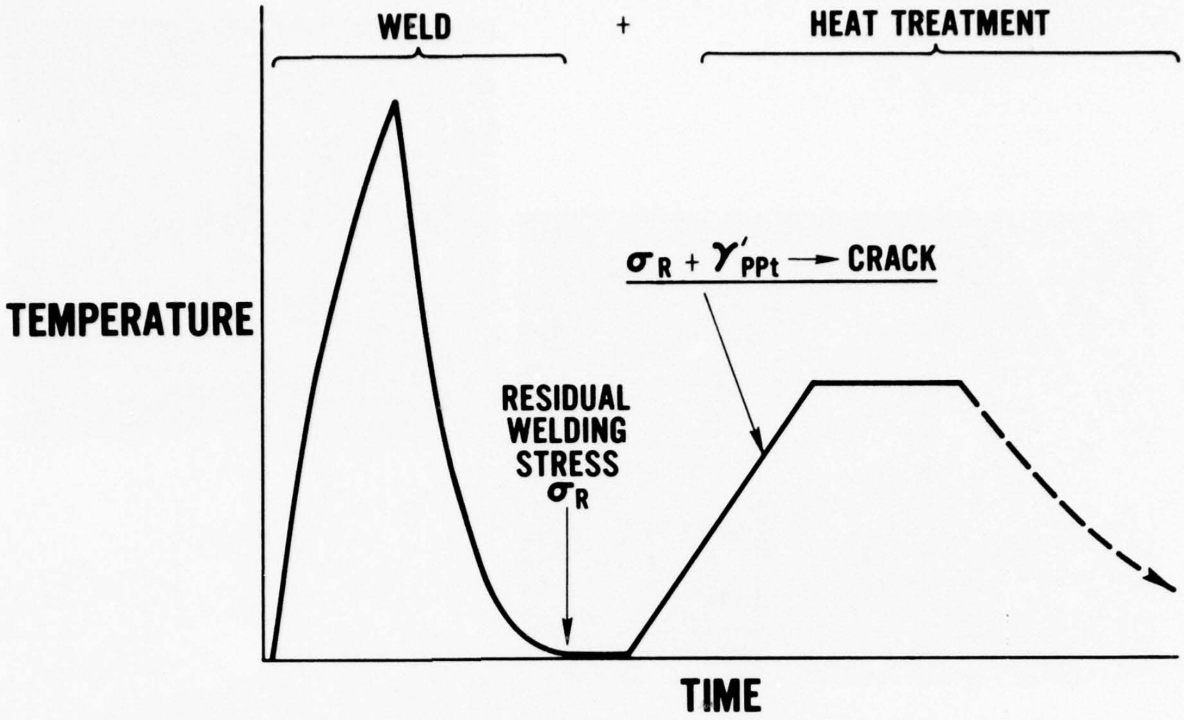

FIGURE 11: SCHEMATIC OF SEQUENCE OF EVENTS TO CAUSE PWHT CRACKING.

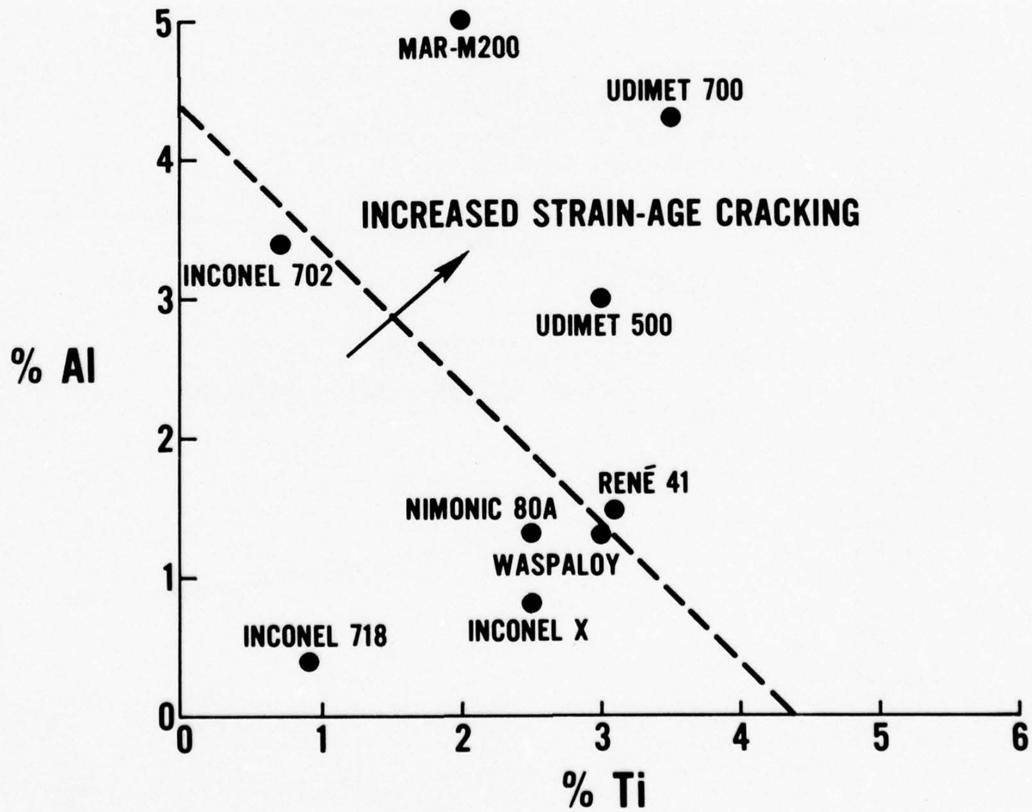

FIGURE 12: EFFECT OF ALUMINUM AND TITANIUM CONTENT ON PWHT CRACKING TENDENCY IN SEVERAL SUPERALLOYS.

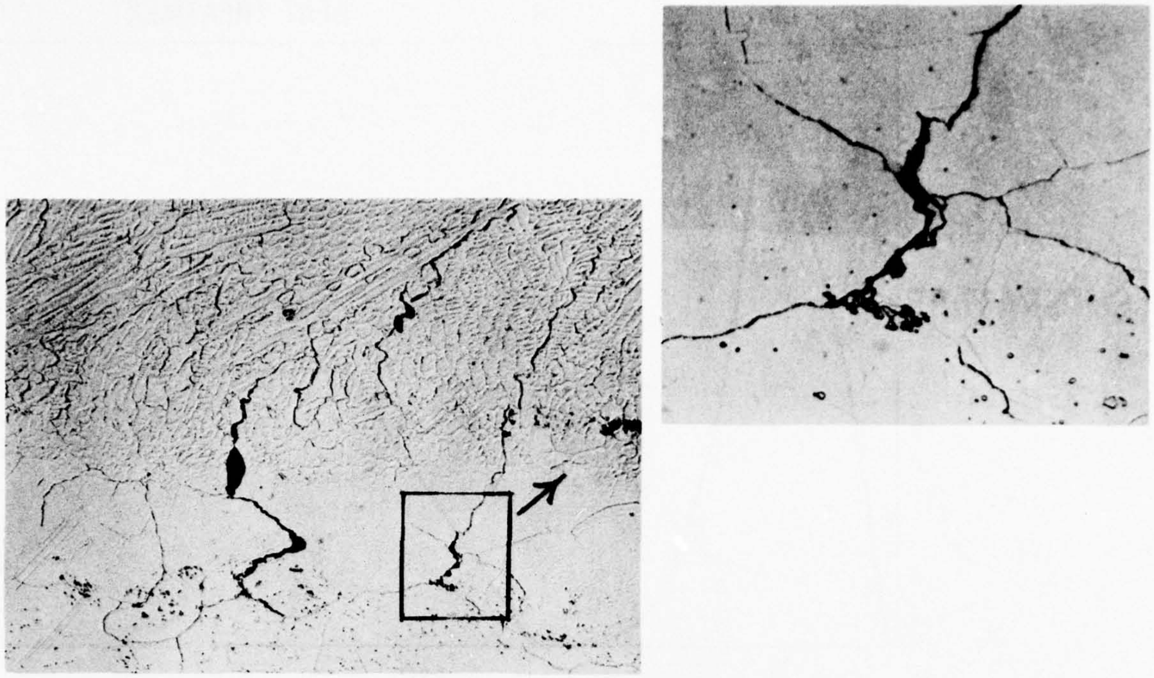

FIGURE 13: INCIPIENT PWHT CRACKING IN SIMULATED, PARTIALLY MELTED HEAT AFFECTED ZONE SPECIMEN IN WASPALOY.

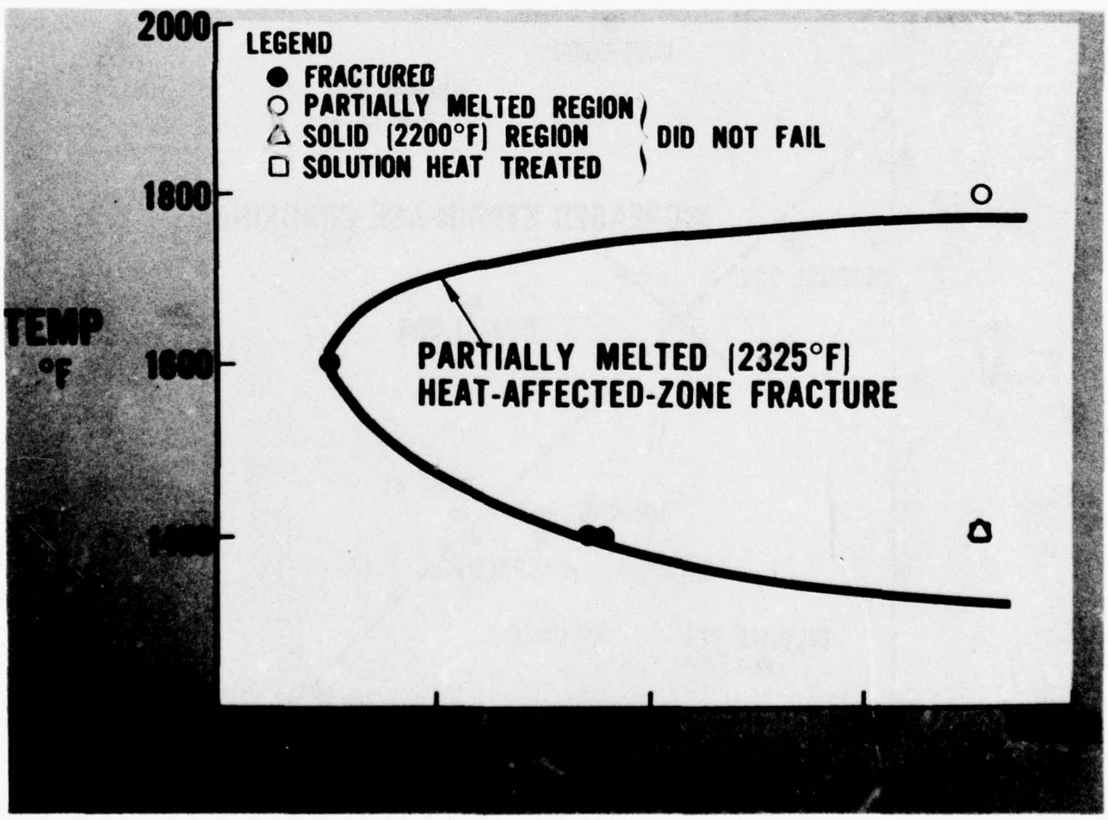

FIGURE 14: PWHT CRACKING TENDENCY FOR TWO SIMULATED HAX REGION IN WASPALOY. TESTED IN CREEP RELAXATION FROM 70 KSI INITIAL STRESS AT TEMPERATURES SHOWN.

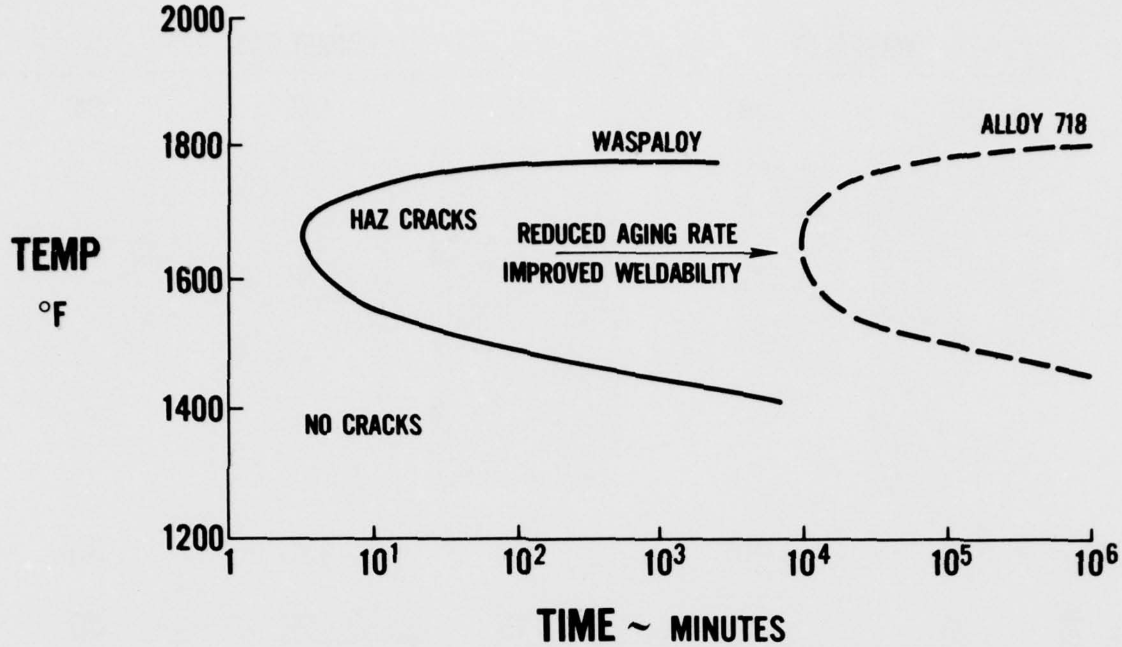

FIGURE 15: "C"-CURVES FOR WASPALOY AND ALLOY 718 SHOWING MUCH GREATER TOLERANCE FOR PWHT CRACKING FOR ALLOY 718 DUE TO SLOWER AGING RATE.

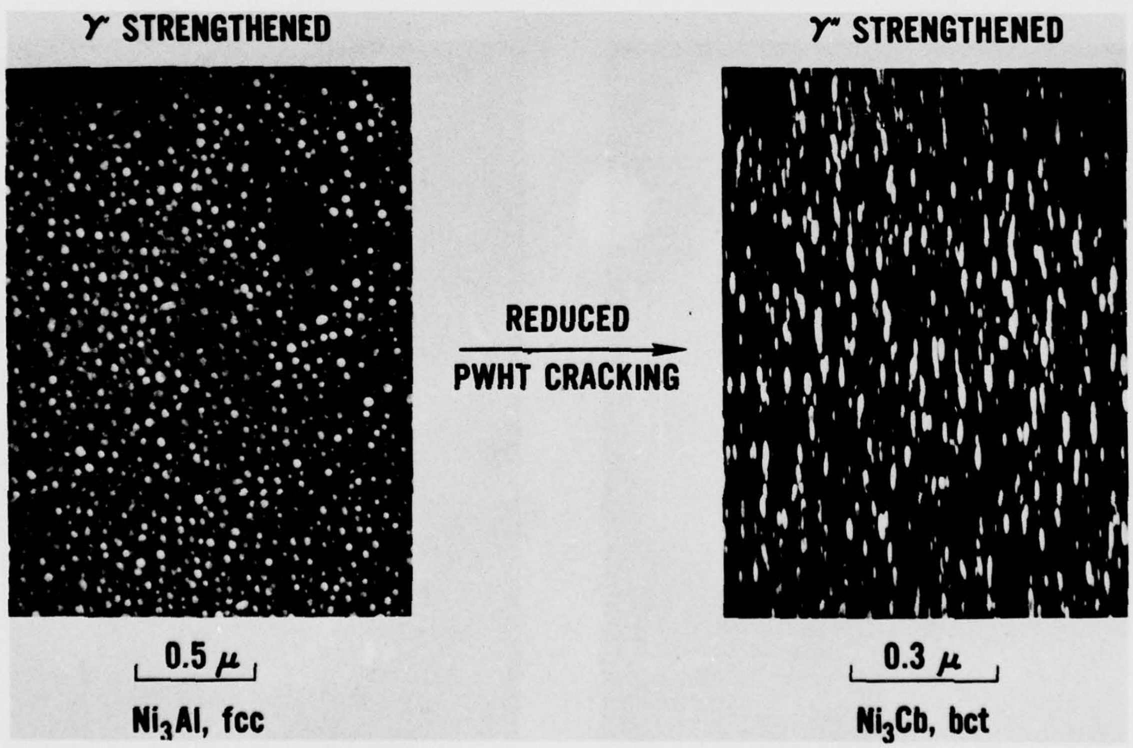

FIGURE 16: COMPARISON OF MORPHOLOGY AND CRYSTALLOGRAPHY OF γ' AND γ'' PRECIPITATES IN SUPERALLOYS.

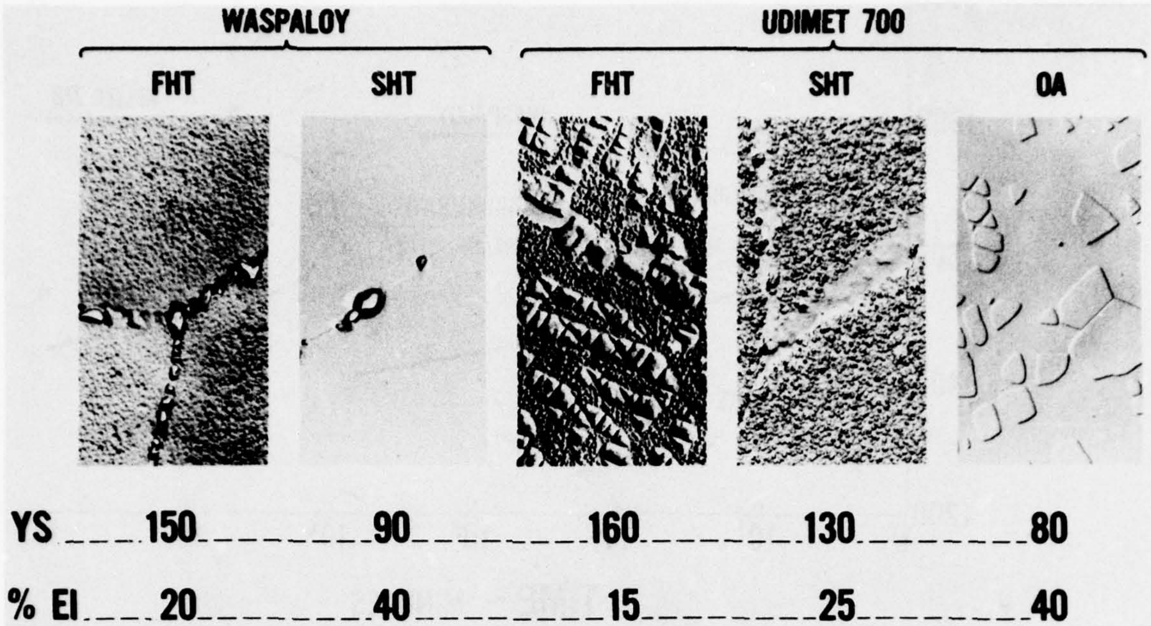

FIGURE 17: INFLUENCE OF HEAT TREATMENTS ON THE MICROSTRUCTURE, STRENGTH AND DUCTILITY OF WASPALOY AND ALLOY 700.

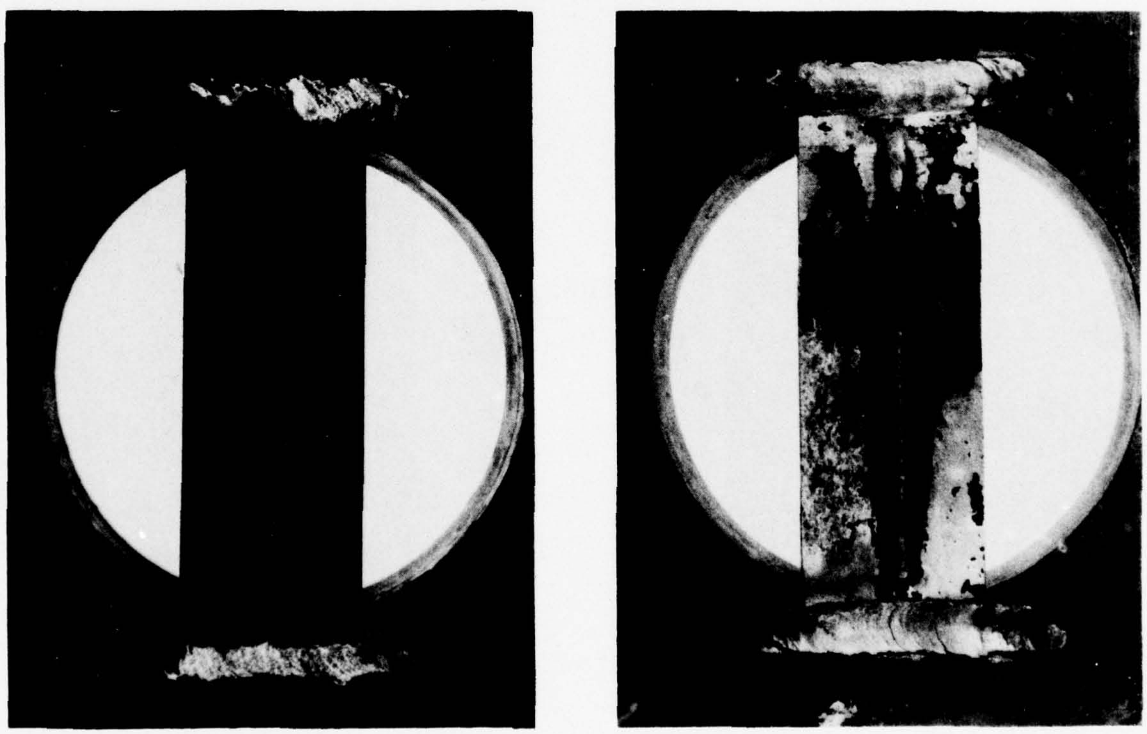

FIGURE 18: MINI-PATCH TEST RESULTS IN ALLOY 700 SHOWING BENEFIT OF OVERAGE HEAT TREATMENT ON PWHT CRACKING. LEFT - SOLUTION HEAT TREAT, RIGHT - OVERAGE HEAT TREAT.

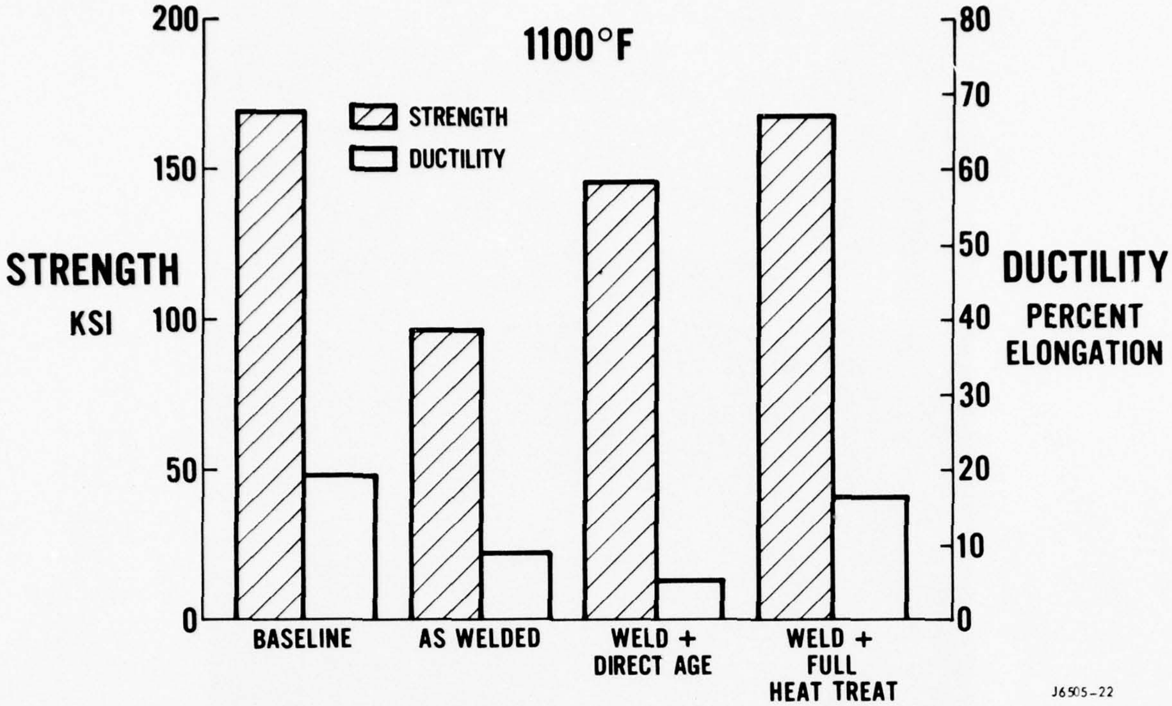

FIGURE 19: COMPARATIVE PROPERTIES OF ALLOY 718 WELDMENTS IN VARIED CONDITIONS SHOWN.

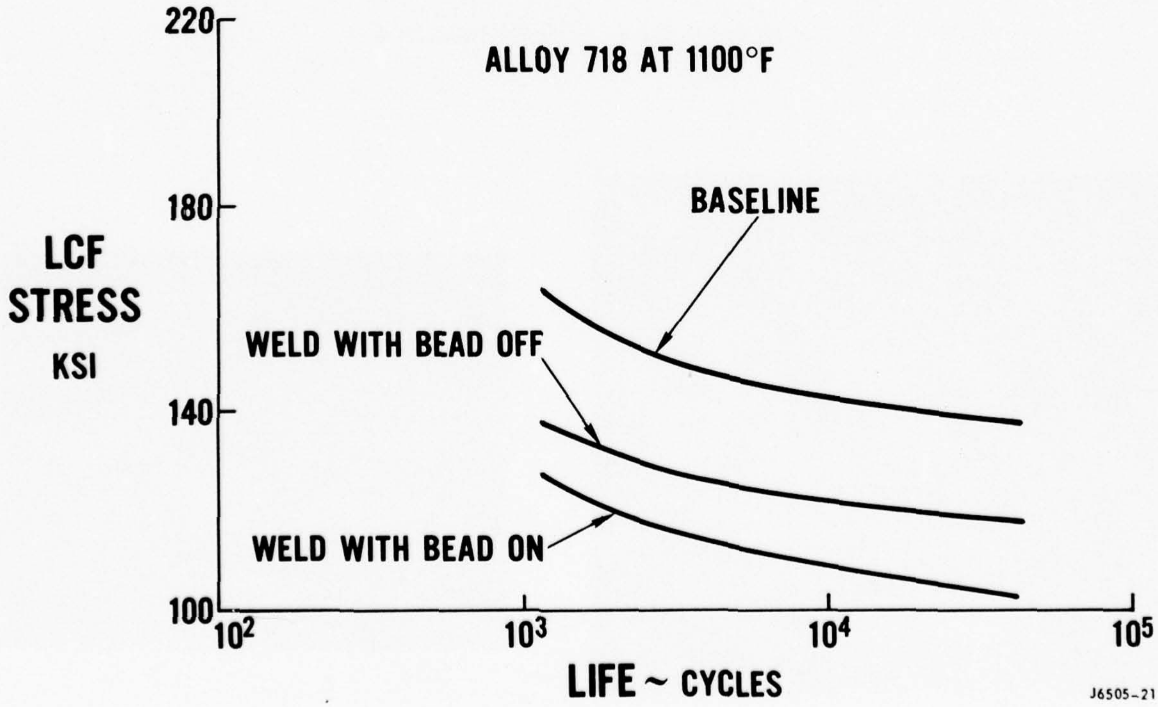

FIGURE 20: LCF PROPERTIES OF 0.060" THICK ALLOY 718 WELDS TESTED AT 1100°F, R RATIO 0.1, TRANSVERSE TO WELD. WELDS FULLY HEAT TREATED.

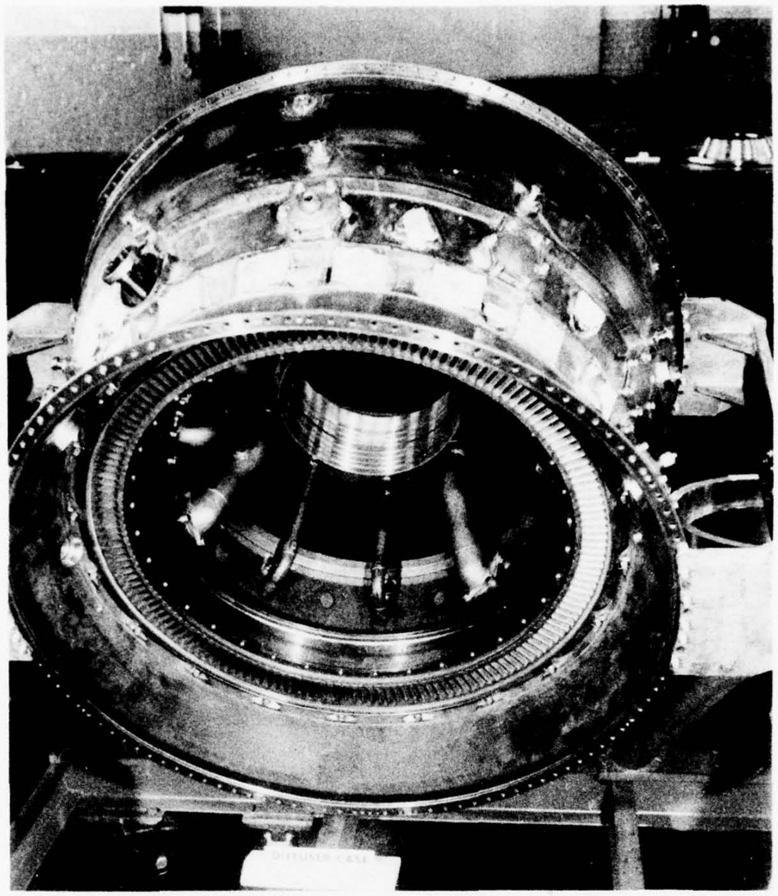

FIGURE 21: A WELDED ALLOY 718 DIFFUSER CASE.

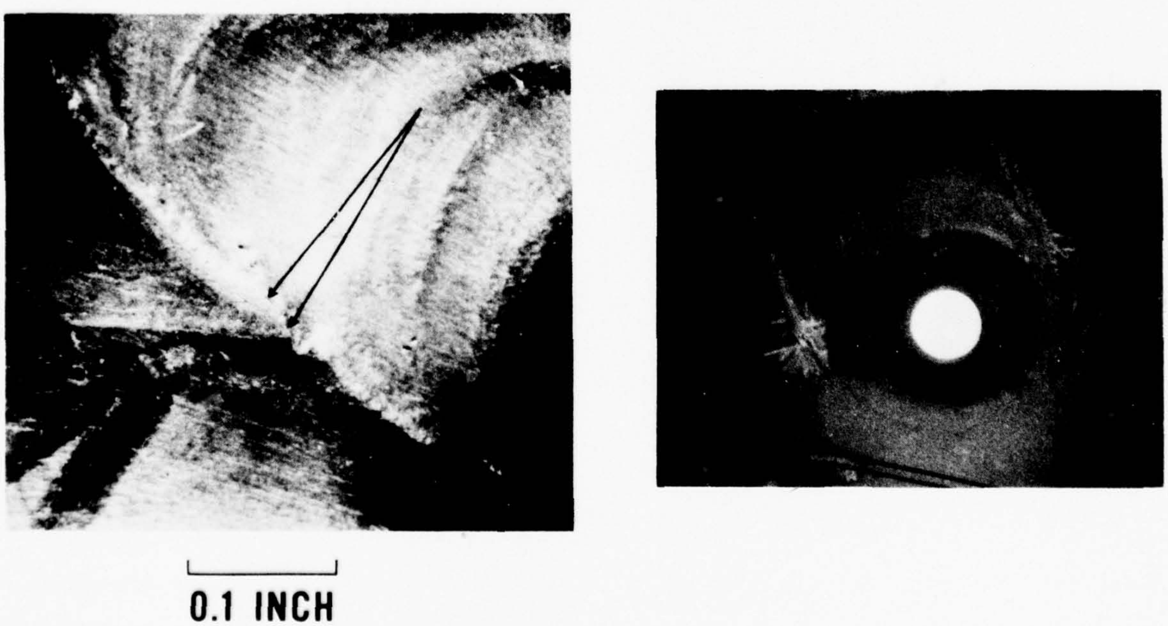

FIGURE 22: REPAIRABLE DEFECT AND LOCAL STRESS RELIEF SET-UP FOR A CASE BOSS REPAIR.

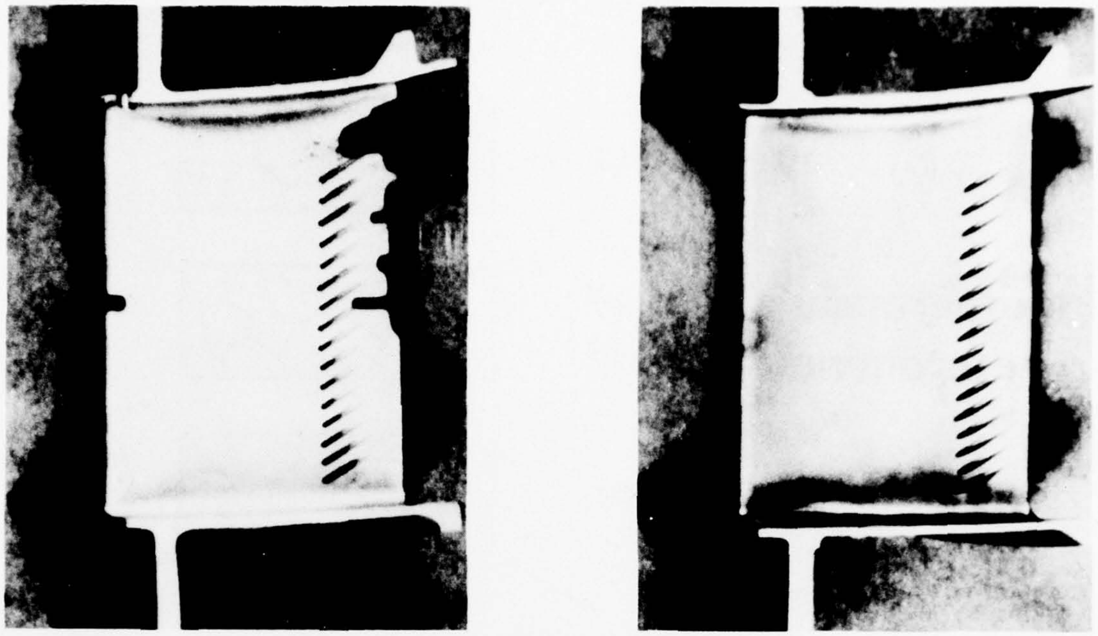

FIGURE 23: TURBINE VANE WHICH IS WELD REPAIRED FOR RESTORATION TO SERVICE. LEFT - CRACKS GROUND OUT; RIGHT - WELDED AND BLENDED TO CONTOUR.

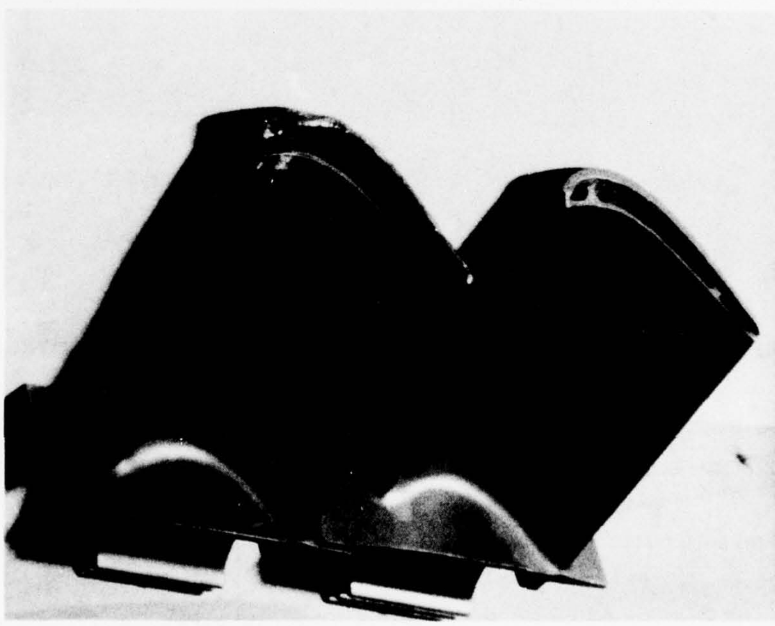

FIGURE 24: TURBINE BLADE TIP WELD REPAIR. LEFT - WELDED TIP; RIGHT - BLENDED TO ORIGINAL CONTOUR.

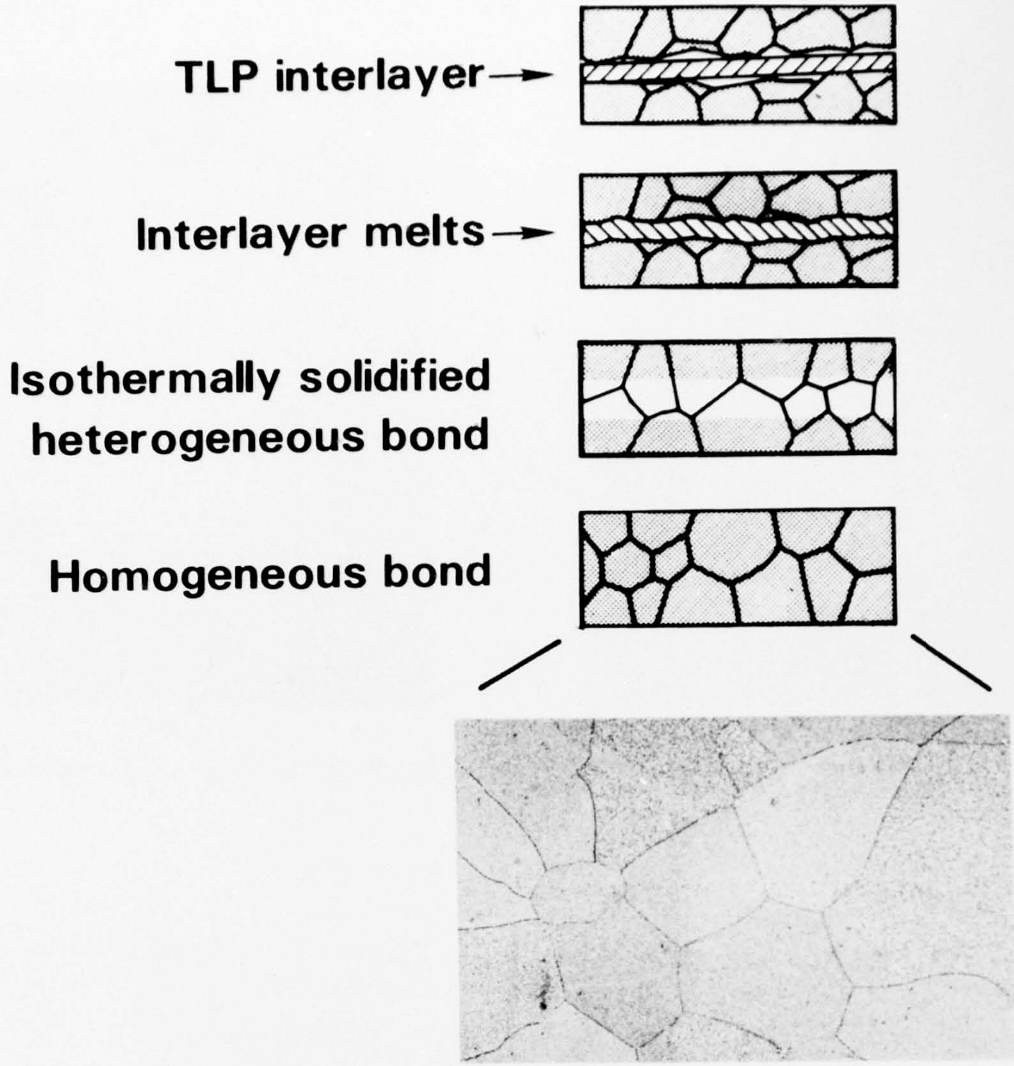

FIGURE 25: FUNCTIONAL DESCRIPTION OF TLP BONDING PROCESS.

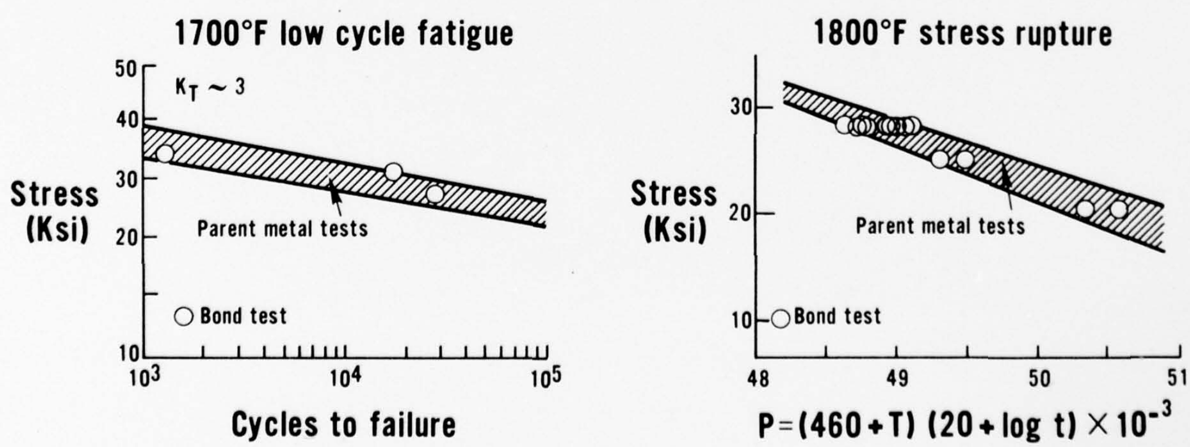

FIGURE 26: LCF AND STRESS RUPTURE PROPERTIES IN TLP BONDS IN ALLOY MAR-M200 + 2% Hf.

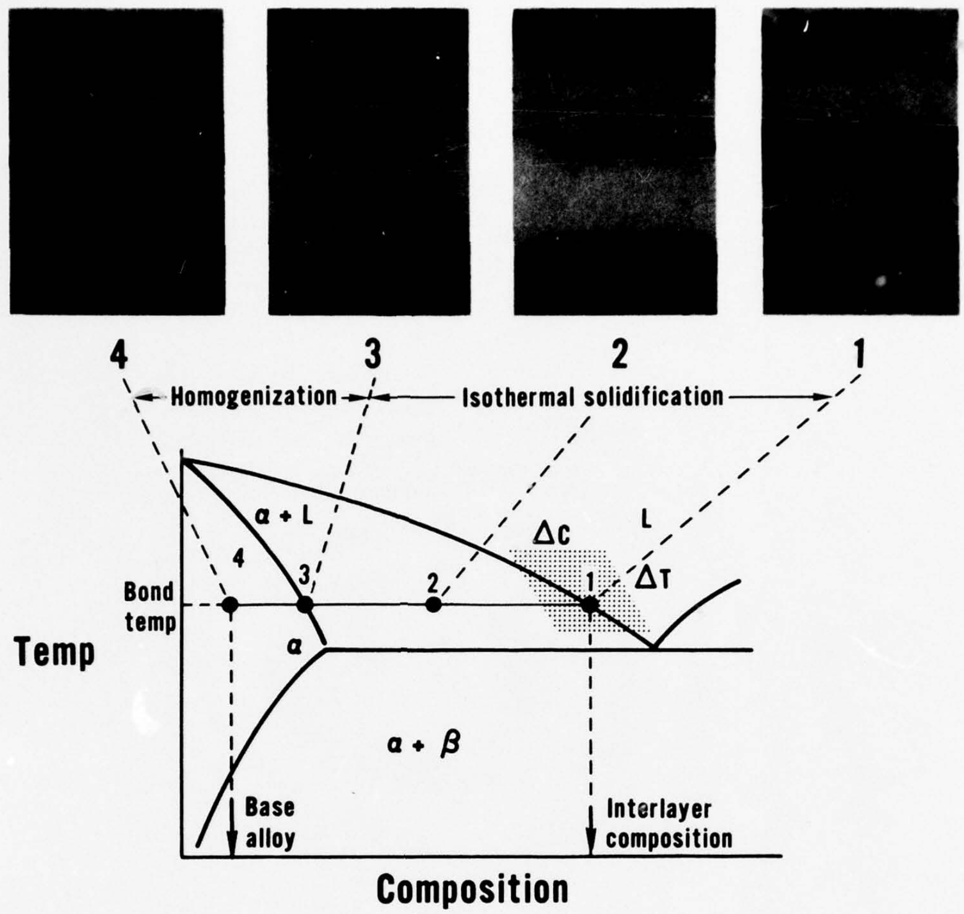

FIGURE 27: THEORETICAL MODEL OF PHASE PHENOMENON WHICH OCCUR DURING TLP BONDING.

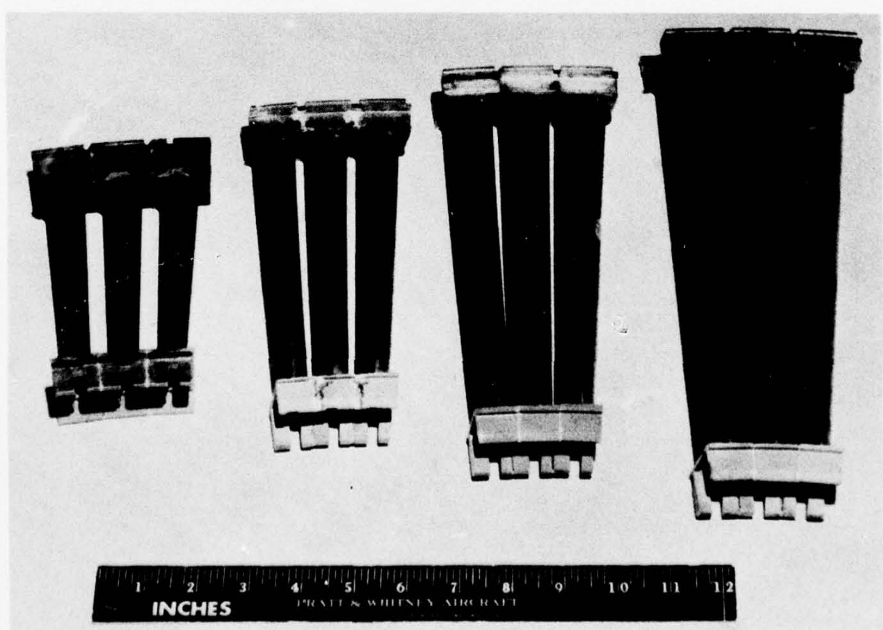

FIGURE 28: TLP BONDED LOW PRESSURE TURBINE VANE CLUSTERS.

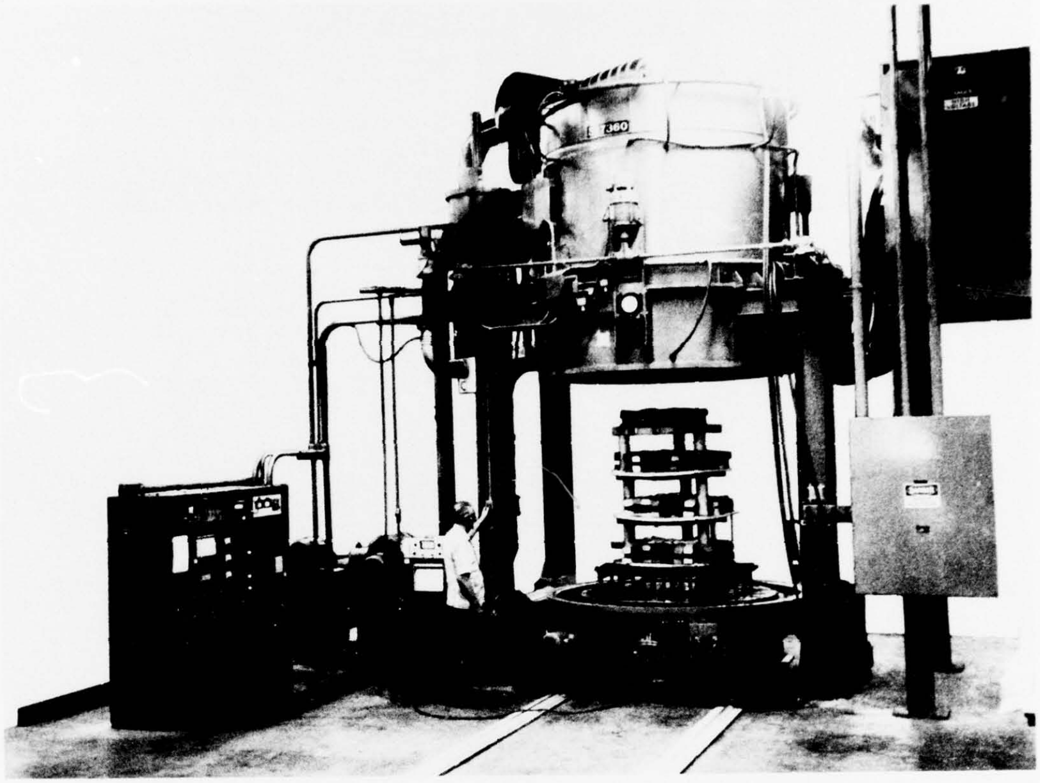

FIGURE 29: VACUUM FURNACE BEING LOADED WITH 200 VANE CLUSTERS FOR TLP BONDING.

RECENT DEVELOPMENTS IN WELDING TECHNOLOGY

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SUMMARY

There are indications that the pace of technical development and innovation is slowing down as a result of the socio-economic changes in the industrial world. This is also true for welding technology. With the development of pulsed TIG and MIG welding and the universal transistorised power source the ultimate step in the development of fusion welding processes appears to have been taken. Despite the fact that high precision welding is now possible, requirements for quality and reliability have now become so stringent that the available techniques are no longer adequate to achieve them. There is, however, scope for improving the economics in the use of the processes. Solid phase welding processes, such as diffusion bonding and friction welding, are largely free from the problems of the fusion welding processes but the research and development effort in these areas is minimal.

International co-operation in welding technology, given the inherent difficulties of communication, is probably at least as good if not better than in many other areas, particularly through the work of the International Institute of Welding. Progress in international standardisation is slow for commercial and legal reasons and even within the European Community differing standards are a serious obstacle to the free interchange of techniques and equipment. This is unfortunately even true for the welding equipment used by the armed forces of NATO.

OBSTACLES TO TECHNOLOGICAL ADVANCE

The introduction of innovation in industry not only requires research and development but investment in new plant. Without investment there is no market for the products of research and development and they will gradually atrophy.

Even before the oil crisis and the recession industrial investment was in decline. The reasons were manifold: high interest rates, declining profitability and consequently lowering in the rate of capital formation, into which further inroads were made by claims to an increasing share of the national product for the purposes of central and local Government by way of rising personal and company taxation. Strong labour unions enforced increases in consumption not matched by increases in production, thus further reducing capital formation for investment.

A further important element is the increasing power of public opinion - sometimes termed the environmental lobby - to prevent the execution of industrial projects or at least to delay their realisation, with the result that vast cost escalations ensue, augmented still further by the cost of public enquiries, legal battles and the imposition of safety measures bordering at times on the ludicrous.

All these factors have combined to slow down the potential market for innovation and investment in R & D is falling. All over the developed world we have witnessed a process of severe reduction in companies' R & D budgets. The overall result has been a slackening if not a total standstill in the pace of technological advance and it would be most surprising if between now and the beginning of the new millenium we were to experience technological change at the rate to which we were witness in the quarter of a century following the end of World War II.

THE WELDING SCENE

This slow-down has also affected the welding field. Not a single new process has been developed during the last decade and the industrial introduction of processes developed since the war, such as electroslag and electron beam welding, has been slow. In the case of electroslag welding, there has in fact been a decline in its application because the requirements for reliability and quality imposed on welded structures have become so stringent during the last decade that they cannot be satisfied with high heat input processes. In the case of electron beam welding, the obstacle to rapid industrial application has been the high cost of investment required.

Some progress has been made nevertheless. This has taken the form of developments and refinements in existing processes to improve their performance in two main directions:

1. Quality and reliability
2. Higher productivity.

These two subjects are of course closely related and interact. They are considered

separately here because the main emphasis in relation to the first objective is on metallurgical and material aspects, whereas the emphasis in the second area is on the welding process side.

QUALITY AND RELIABILITY

Material Aspects

We have at least in the West experienced a process of continuously stiffening requirements for quality and reliability. Methods for non-destructive examination have been improved to an extent where smaller and smaller defects can be detected, and developments in fracture mechanics have provided criteria relating the size of a defect to the potential risk of failure. This is reflected on the one hand in the imposition of much tighter specifications for the chemical composition of parent metal and weld metal to avoid such defects as hydrogen-induced heat-affected zone cracking in steels, solidification cracking, reheat cracking and porosity, and on the other hand in requirements for minimum notch ductility - in the case of steels not only for parent metal but weld metal and heat-affected zones - and for proof of adequate through-thickness ductility to prevent lamellar tearing. These requirements in turn have imposed much more stringent control of the welding process, particularly in respect of joint preparation and heat input, and much more severe supervision of the operator.

Process Aspects

One of the important parameters requiring control is heat input. With conventional power sources this is extremely difficult, if not impossible, particularly in situations where as a result of gradual heat build-up in the workpiece the heat input has to be diminished as welding proceeds.

The development of pulsed TIG and MIG welding, in which heat input is not produced as a continuous stream but in discrete quanta, was the first step towards the achievement of high precision in fusion welding operations. It is worth noting, however, that this increased precision was achieved at a price. Up to that time, current, voltage and wire diameter or electrode size were the only relevant variables. In pulsed TIG or MIG welding further variables are introduced: the ratio between background and peak current, the pulse duration and the time interval between pulses, which must be chosen correctly if the optimum results are to be achieved. Even the shape of the current pulse is important.

The most recent development and quite possibly the ultimate stage beyond which no further progress in arc welding seems possible, is the Transistor Power Source. This is fundamentally a high-fidelity, high-power amplifier capable of reproducing any waveform. Welding current can be controlled to within 0.5% of the maximum for variation in line voltage of up to 20%. Voltage-current characteristics can be varied from constant current for TIG welding to constant voltage for MIG welding. Current rise for short-circuit at the output terminals can be varied continuously from 50 μsec. to 100 msec. Pulse frequencies for square waves up to 10 kHz are possible. Utilisation of such high frequencies in the welding of small-bore aluminium tubing used in the aerospace industry has been claimed to result in a greatly improved grain structure and the elimination of hot cracking.

One of the first important industrial applications was in the production of tube-to-tube plate joints for a stainless steel heat exchanger for nuclear power application in which maximum tolerable crack size was limited to 25μ and the contour of the weld cross-section was required to lie inside a fixed, smooth geometric contour. The 40mm diameter, 4mm thick tubes were inserted from one side for a distance of about 1mm into the 175mm thick stainless steel tube plate and TIG welded by a rotating precision torch inserted from the other side. Nearly 10,000 welds have been made this way with a reject rate of only 0.03%. A cross-section through two experimental joints is shown in Fig. 1. The weld contour on the left is unacceptable as lying outside the specified profile due to slight over-roll of the weld. This weld was produced with a conventional magnetic amplifier power source and the defect was caused by 2% main voltage fluctuation.

Special advantages can be obtained in the use of the transistorised power source in plasma welding. Under continuous current operation high welding speeds can be obtained in the "keyhole" mode of plasma welding but a careful balance between current, plasma gas flow and traverse speed must be maintained which can be disturbed by local variation in the material and, of course, positional welding is impossible. If the current is pulsed the weld pool solidifies at the low background level but the keyhole does not close up if the plasma flow is maintained so that the weld pool is easily reformed when the current pulse is injected. The square edge butt weld of the 950mm diameter tube of 3mm wall thickness shown in Fig. 2 was made in the horizontal vertical position.

One very tiresome problem frequently experienced in production using conventional power sources is that settings for welding procedure variables obtained by careful experimental work in the laboratory to achieve a certain objective fail to produce the same result consistently when transferred to a production line because similar power sources, even of the same make, have slightly variable characteristics for the same settings and are affected by changes in the mains power supply. The transistorised power source does not suffer from this defect and the same settings will reproduce the same results with great accuracy. It is in the same class as a high precision machine tool.

In this context an interesting observation is perhaps not out of place. Ignorance about welding is so widespread and profound in industrial management that even companies replacing their machine tools frequently and maintaining and tending them with the greatest care will continue using old welding plant, badly maintained, as long as it shows a spark of life by producing an arc, and are then surprised and irritated if the results do not come up to expectations.

Precision MIG welding, of course, also requires much greater precision in wire feed speed and the conventional double pressure roll feeding system, apart from deforming the wire, tends to slip and must be replaced with a capstan system, shown in Fig. 3. The introduction of this very low inertia system has opened the way to synchronising wire feed with current pulse. Wire feed pulses varying from zero to 17mm/sec can be produced at frequencies of approximately 8Hz. If this is used with a transistorised power source with a square wave pulsing capacity of 1×10^6 A/sec and the current is pulsed in synchronism with the wire feeder between 30 and 300A, welds can be made with a penetration equal to that for 300A continuous current but with a total heat input corresponding to only 75A. Thus butt joints in steel plate can be made without backing or root gap.

The great advantages of these new precision welding systems are the accurate control of penetration, bead width, heat input, solidification and weld metal structure, permitting the welding of materials greatly differing in thermal capacity as the result of differences in mass, thickness or thermal conductivity. At the same time precise values for a much larger number of welding parameters require to be determined experimentally. Indeed, the new power source is not unlike a computer; it can be programmed by a mini-computer but requires to be fed with the correct software and the production of this software requires a formidable effort of experimental work. Some applications of the transistorised power source are shown in Fig. 4.

Two further but quite different developments in gas-shielded welding are AC MIG and twin electrode switched MIG welding. In the latter process the arc is switched alternately between the workpiece and one or other of two electrodes in close proximity, as shown in Fig. 5a and b. A great variety of weld bead profiles can be produced, as shown in Fig. 6.

The deep "finger" type of penetration for high current welding can be avoided by better wetting in and side-wall fusion and a smoother bead profile can be produced. In some respects the process is an electrical alternative to the weaving motion of the manual welder and makes complex mechanical torch weaving devices unnecessary.

The system is not limited to two electrodes or indeed to MIG welding. Combinations of MIG and TIG are possible and there is considerable potential for practical application of the system. It offers the possibility of mechanised vertical welding of thick material because the better heat distribution limits the size of the weld pool. It permits higher deposition rates with no tendency to lack of side-wall fusion.

AC MIG welding is possible with high open circuit voltage of over 250V RMS for arc stabilisation but power sources with such high open circuit voltage would constitute an unacceptable safety hazard. With a suitable reignition system by pulse injection the open circuit voltage can be reduced to 70V RMS. Metal transfer occurs mainly during the electrode positive half-cycle but at high currents metal transfer occurs also during the electrode negative cycle. This has the beneficial effect of widening the current range of operation, as shown in Fig. 7 which illustrates the relationship between wire feed speed and current for DC-MIG with electrode positive and AC-MIG welding for 1.6mm aluminium wire. Butt and fillet welds produced by AC MIG welding in aluminium are shown in Fig. 8a, b, c and d. For this material the deposition rate is at least 50% greater than for DC at the same current. One further advantage is the smaller weld pool so that positional welding at higher currents is much easier. The deep finger penetration with high current DC welding which is frequently associated with porosity is absent and so, of course, are magnetic effects which are so frequently a nuisance in DC welding.

Both processes, switched multi electrode welding and AC MIG welding, are developments with scope for increasing deposition rates and therefore productivity, in addition to offering higher weld quality under certain circumstances.

IMPROVING PRODUCTIVITY

EB and Laser Welding

The high productivity process par excellence is electron beam welding. It has now been developed to a point where steel plate up to 150mm in thickness (shown in Fig. 9) can be welded in one pass at speeds of 150mm/min. Higher speeds, albeit so far for thin material, can be achieved in laser welding. Both processes have the advantage of not requiring filler material, which constitutes a further saving. The principal advantage, however, appears to lie in the potential for greatly reducing the statistical incidence of defects. In conventional fusion welding processes the number of variables requiring control to achieve high quality is large because the chemical composition and cleanliness of the wire and the purity of the gas in gas-shielded processes and the purity and consistent quality of the ingredients in the flux require stringent control if defects are to be avoided. In addition, there is the variability of skill and conscientiousness of the operator. Electron beam and laser welding are essentially automatic processes using high-precision electronic equipment and requiring no operator skill. Hydrogen cannot be

introduced into the weld and defects can arise only from variability in the quality of the material to be welded, potential advantages which one would have thought far outweigh the high capital cost of the equipment. Nevertheless, for reasons given earlier electron beam welding and laser welding have made very slow progress.

Robots

Efforts to replace manual skill in conventional arc welding are intensifying. The development of the programmable transistorised power source has greatly enhanced the scope for using industrial robots to move the welding torch which can be constructed and programmed to follow complex joint lines in space. The precision in the movement of robots is however inadequate to maintain the arc exactly over the joint line and at the correct distance. With a suitable sensing device and feedback it should be possible to overcome this problem. If the torch is energised from a transistorised power source and "the process tolerance limits" as defined below are known, the correct welding parameters within these tolerance limits can be furnished as a function of torch position and travel speed.

Profess Tolerance Limits and Optimisation

If the welding parameters such as wire diameter, voltage, current, wire feed speed and others in a process are varied at random, certain combinations of parameters will produce acceptable welds and others will produce unacceptable welds. If the results of such experiments are plotted in a series of diagrams relating two variables, the values for the parameters giving acceptable welds will lie within a restricted area defining the degree of variation in the parameters that is acceptable. A typical diagram of this type is shown in Fig. 10 for a square edge butt joint made in 12.7mm thick steel by submerged arc welding. The highest welding speed and therefore the highest productivity would be obtained at approximately 1200 Amps. The diagram at that current level peaks, which means that at the highest travel speed the current must be held absolutely constant. Even a slight reduction in current would produce lack of penetration and an excess of current would produce burn-through. If this condition cannot be maintained and the equipment is so unreliable that current may fluctuate by say 100A either way, the maximum travel speed will drop to half. The same diagram shows that if the voltage is allowed to vary from 30V to 28V acceptable welds can only be produced at much lower travel speeds and currents. These findings emphasise the adverse effects on productivity resulting from the use of out-of-date or badly maintained welding equipment.

Results from a similar investigation of the TIG welding of 0.9mm and 1.6mm thick stainless (AISI 316) steel sheet in the flat position have revealed some rather startling facts. One series of experiments was carried out in which the relation between travel speed and the angle of inclination of the torch to the workpiece was examined. The results are shown in Fig. 11. With the torch vertical (0^o) the maximum travel speed attainable to produce acceptable welds is approximately 40mm/sec but to weld at this speed requires the current to be kept constant at 150A. Even small deviations either side from this value will produce lack of fusion or an unstable weld pool. By inclining the electrode 45^o the welding speed can be more than doubled and the tolerance limits for current are increased by nearly 50A either side of 300A.

WELDING WITHOUT FUSION

Brief reference has been made earlier to the problem of meeting steadily stiffening requirements for perfection, and mechanical properties in the weld and the heat-affected zone matching those of the parent metal, by the fusion welding processes. It is in the nature of fusion welding that the weld and heat-affected zone must differ from the parent metal. The refinements in process technology briefly referred to in this paper are not adequate to do more than alleviate this problem because it is essentially a function of parent metal composition, purity and homogeneity and its response to high temperatures.

This problem area, which makes fabrication by fusion welding increasingly difficult, complex and costly and occasionally almost impossible, must gradually shift emphasis to processes not requiring the attainment of fusion temperatures. Once it becomes more generally realised that we are at the end of the road as far as fusion welding is concerned and that it is just not within the inherent capability of fusion welding to satisfy the stringent requirements now imposed over an ever widening field of construction, we shall have to turn our attention to alternatives.

Resistance welding, though still involving some liquefaction, does not suffer to the same extent from material problems which beset the fusion welding field. Moreover, for resistance spot welding and flash welding automatic quality control employing feedback has reached a very advanced stage of development. Considering that for many decades R & D effort in this field has been minute, the possibility that sustained and greatly intensified effort to broaden its range of application by using quite novel power sources such as the homopolar generator could yield quite startling results deserves serious consideration.

Diffusion bonding has been around for a very long time and considering the high quality of joints that can be produced and the almost total absence of metallurgical problems, changes in mechanical properties and defects, it is an attractive process that deserves

much greater attention that it has received. Compared with fusion welding it seems so natural and simple a process of joining and it is surprising that it has not found more widespread application and has attracted so little R & D effort.

The great advantages of solid-phase joining processes are perhaps best illustrated by friction welding. Metallurgical problems are almost non-existent and a wide variety of dissimilar metals can be joined; defective welds can be avoided by using automatic quality control and monitoring. It is of course limited at present to the welding of cylindrical or nearly square components to each other or to reasonably flat surfaces. A good illustration of the application of friction welding is shown in Fig. 12. A dozen high-alloy steel studs are attached by friction welding to a machined cylindrical component in four rows of three spaced at 90° round the circumference. A special machine, shown in Fig. 13, was designed and constructed in order to maintain the very fine dimensional tolerances required not only for the finished lengths of the studs but for the spacing in both the axial and circumferential directions.

Radial friction welding of tubes and pipes is another interesting development. A wedge-shaped ring is rotated in a double-vee preparation formed at the ends of the stationary tubes to be joined, identical to that which would be required for a fusion weld; during rotation radial pressure is applied to the ring, forcing it into the joint preparation and welding it to the tube ends. Such a weld is almost indistinguishable in appearance from a fusion weld but is guaranteed to be free from defects and to have the same mechanical properties as the tube (Fig. 14).

CO-OPERATION IN RESEARCH

The decline in R & D that has taken place all over the developed world has placed increased emphasis on the possibilities of international co-operation. The International Institute of Welding, with the General Secretariat in London and the Scientific and Technical Secretariat in Paris, is an organisation which is potentially ideally suited to fostering such co-operation. Thirty-seven countries, listed in Appendix 1, are participating in its work. It was founded in 1948 and is organised in 16 Commissions, to which each of the participating countries has the right to appoint a delegate and a number of experts and observers. The IIW holds an annual meeting, each time in a different country, and most of the time is devoted to meetings of the Commissions which are not held in public. It is obvious from the list of Commissions given in Appendix 2 that not all Commissions are concerned with research, and research and development is a predominant topic in a relatively small number of Commissions, such as Commission X on Residual Stresses and Brittle Fracture and Commission XIII on Fatigue. The Commissions concerned with research endeavour to promote some degree of alignment of national programmes and greatly foster the exchange of information. There are limits, however, to what can be achieved because the International Institute's income from subscriptions collected from member countries is quite modest and scarcely covers the administrative expenditure incurred in running any international organisation. Nevertheless the discussions taking place within the framework of the Commissions have an indefinable but undoubtedly considerable influence on the thinking of those participating in the work. A large number of reports emanating from the different countries and describing work in those countries during the past year are discussed at Commission meetings and it is the duty of national representatives to keep others, who are unable to participate in the Commission meetings personally, informed on what goes on. There is, in the author's opinion, no other international organisation with such extremely modest funds at its disposal that is equally effective in fostering international discussion and a flow of information.

The Welding Institute in the United Kingdom, of which the author had the honour of being Director General until last month, promotes co-operation in a different way. It is supported by approximately 700 individual industrial organisations in 28 countries, listed in Appendix 3, paying annual subscriptions which are pooled and expended in the pursuance of research projects of common interest to large sections of its membership. Most of the technical topics touched upon in this lecture formed part of this programme and the results are communicated to Members in the form of research reports and also in a monthly Bulletin published by the Institute but available to Members only. The programme itself is defined in great detail and supervised by a Board consisting of representatives of the member organisations.

In addition to the general programme, specific projects which are of interest only to industrial organisations operating in specific areas, such as for instance the pressure vessel field, are carried out under research contracts financed by those companies specifically interested in the particular topic and controlled by their representatives. One such project recently completed, and in which companies from several industrial companies participated, was an investigation into the weldability problems encountered in the application of high-power electron beam welding of thick steel plate, such as is used in the pressure vessel industry. The results of this work are of course confidential to the companies participating in the project.

Research contract work is, of course, also carried out for individual industrial companies and Departments of Government not only in the United Kingdom but also in other countries.

After the entry of the United Kingdom into the European Economic Community The Welding Institute and the Universities of Ghent and Aachen took the initiative in forming the

European Research Institute for Welding, membership of which is open to other independent research organisations entirely devoted to welding technology within the European Community. The object of the European Institute is to promote collaborative welding research within the Community and to strengthen the capability of each of the participating Institutes by making available to each of them the facilities of the others. This has already proved of great benefit in the course of an investigation now in progress and concerned with the improvement of the notch ductility of welds and heat-affected zones in electroslag welding of heavy steel fabrications.

STANDARDISATION AND INSPECTION

Progress in standardisation in the welding field is inevitably slow because the adoption of common standards in different countries frequently has far-reaching commercial implications. The adoption of a new safety standard for welding equipment, for instance, may consign a very large quantity of welding equipment to the scrap-heap. New standards may also involve extensive redesign and retooling, changes which no enterprise will view with equanimity, particularly in a period of severe financial stringency. It is indeed surprising, if not disheartening, to see that even within the original members of the European Economic Community none of the technological barriers to the free exchange of goods, which is one of the avowed objectives of the Community, have been touched, let alone eliminated, and there is no sign that a start is being contemplated in the removal of such barriers in the welding field. This applies not only to equipment used for cutting and welding and to consumables, but also to parent materials and to the products made by fabrication, such as pressure vessels. For instance, the design requirements for pressure vessels are different in almost every country of the Community and of course are different again from those used in Canada, the United States or Japan. This seems highly illogical because it is difficult to see why what has been used in perfect safety in one country for many years should not be equally usable with the same degree of safety in any other country. For instance, bulk storage vessels for CO_2 used in welding can be much thinner in Germany than in the United Kingdom; regulators for gas bottles used in the United Kingdom are considered unsafe in Germany and the list of similar discrepancies is endless.

International standardisation is, of course, an entirely voluntary activity carried out under the aegis of the International Standards Organisation and it is not surprising that progress in the formulation of international standards is painfully slow considering the important and quite legitimate interests involved and the fact that the technical assistance that can be rendered to standards committees by permanent staff is extremely limited because the financial resources available for standardisation activities, not only on an international scale but also on a national scale, are woefully inadequate in relation to the magnitude of the task to be performed.

One particularly weak area is that of standards for inspection procedures and the application of quality standards. The qualification required by inspection personnel is generally ill-defined and there are no common training or examination requirements for such people. In the United Kingdom a national system for certification has been introduced which at least guarantees that those charged with the application of inspection, particularly radiography and ultrasonics, reach a minimum standard of competence. Similar systems do not, however, exist anywhere else.

There are also very wide differences in the quality standards required to be attained in different countries and sometimes even those applied by different inspection authorities in one and the same country. Despite great perseverance on the part of one of the Commissions of the International Institute of Welding to formulate proposals for an international acceptance standard for weld quality, these endeavours have not yet come to fruition. In the United Kingdom a committee of the British Standards Institution has been in being for seven years and has produced a draft on defect acceptance standards which, to put it mildly, has not been received with great enthusiasm by any of the organisations directly affected by it, despite the fact that all these organisations were directly represented on the committee formulating the draft. The difficulties in reaching common ground in this area are, of course, formidable and are possibly only another indication of the problem referred to earlier, that we have entered a period where the requirements for fusion-welded joints have gone considerably beyond that which fusion welding processes can be expected to deliver. It would not be surprising if fusion welding were replaced by other processes long before such common standards of acceptance have been agreed.

The author cannot claim close familiarity with welding equipment used by the armed forces within the North Atlantic Treaty Organisation but from such scraps of information as have come to his attention it is obvious that no attempt has been made to make welding equipment or consumables freely interchangeable. To what extent this might constitute a handicap in times of conflict is for others to consider. It is natural, of course, for each country to place large government contracts for equipment with its own industry and to use as far as possible the products commercially available within the country concerned. Since very little progress has been made, as pointed out earlier, in adopting common standards even within a limited number of countries such as the European Economic Community, it is not surprising that this state of affairs is reflected in the military field.

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APPENDIX 1

Countries participating in the International Institute of Welding

Argentina
Australia
Austria
Belgium
Brazil
Bulgaria
Canada
China
Czechoslovakia
Denmark
Fed. Rep. Germany
Finland
France
German Dem. Rep.
Hungary
India
Iran
Ireland
Israel
Italy
Japan
Netherlands
New Zealand
Norway
Poland
Portugal
Rumania
South Africa
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States
USSR
Uruguay
Yugoslavia

APPENDIX 2

Commissions of the International Institute of Welding

Commission I	:	Gas Welding, Brazing and Cutting
Commission II	:	Arc Welding
Commission III	:	Resistance Welding
Commission IV	:	Special Welding Processes
Commission V	:	Testing, Measurement and Control of Welds
Commission VI	:	Terminology
Commission VIII	:	Hygiene and Safety
Commission IX	:	Behaviour of Metals subjected to Welding
Commission X	:	Residual Stresses and Stress Relieving, Brittle Fracture
Commission XI	:	Pressure Vessels, Boilers and Pipelines
Commission XII	:	Flux and Gas Shielded Electrical Welding Processes
Commission XIII	:	Fatigue Testing
Commission XIV	:	Welding Instruction
Commission XV	:	Fundamentals of Design and Fabrication for Welding
Commission XVI	:	Welding of Plastics
Study Group 212	:	Physics of the Arc and other high energy Sources used for Welding

APPENDIX 3

Countries with Organisations in Research Membership of The Welding Institute

United Kingdom

Australia
Argentina
Bahrain
Belgium
Brazil
Canada
Denmark
Fed. Rep. Germany
Finland
France
India
Irish Republic
Italy
Japan
Kuwait
Luxembourg
Malta
Netherlands
New Zealand
Nigeria
Norway
Portugal
Singapore
South Africa
Spain
Sweden
Switzerland
USA

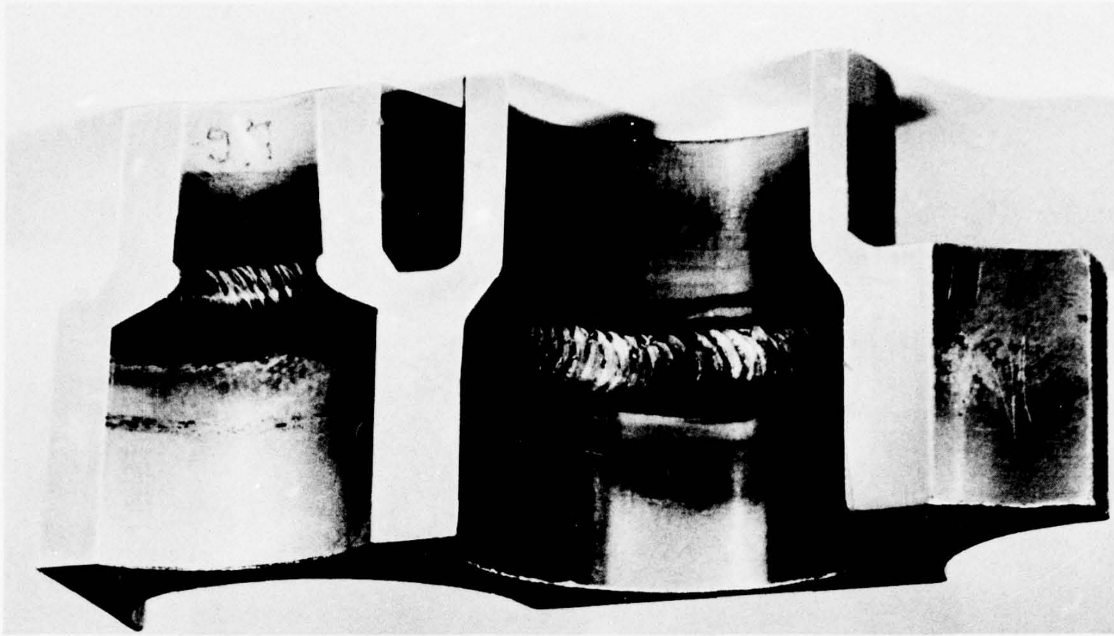


FIG. 1 Tube to tube plate joints in stainless steel heat exchanger for atomic power application. The weld on the left is unacceptable because the weld contour of the cross-section is outside the prescribed limits. It was made with a power source using a magnetic amplifier. The weld shown on the right is within the prescribed contour and was made with a transistorised power source.

FIG. 2 Pulsed keyhole plasma weld in 950mm diameter, 3mm wall thickness stainless steel tube of type AISI 304.

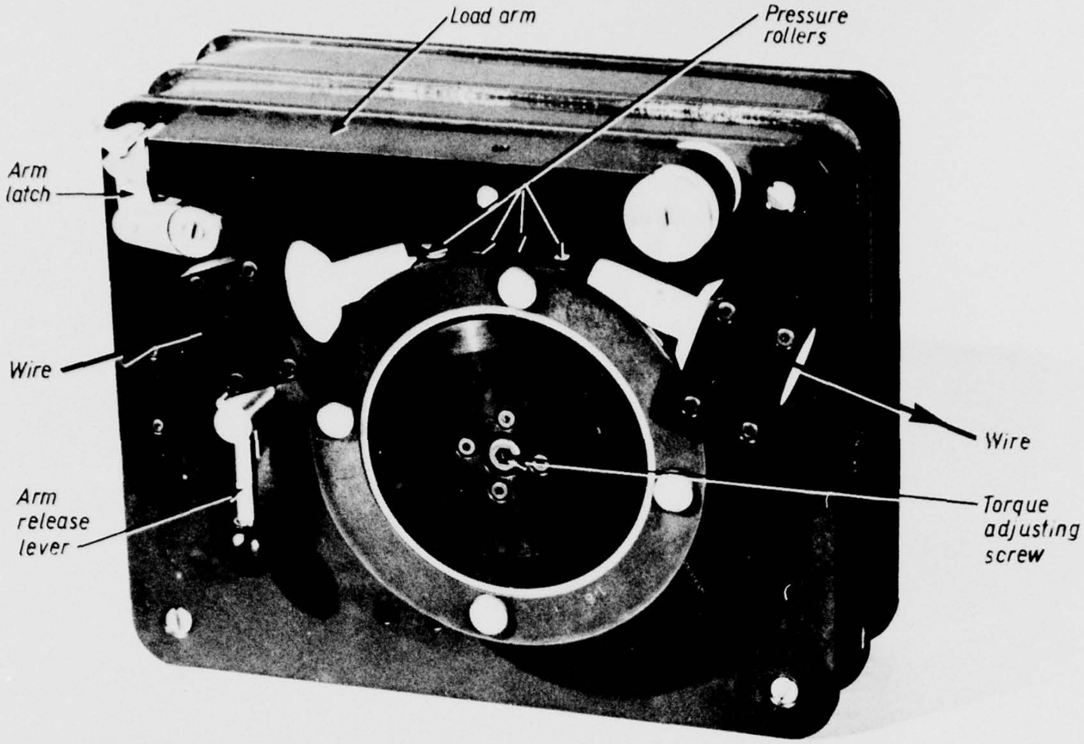


FIG. 3 Capstan drive precision wire feeder.

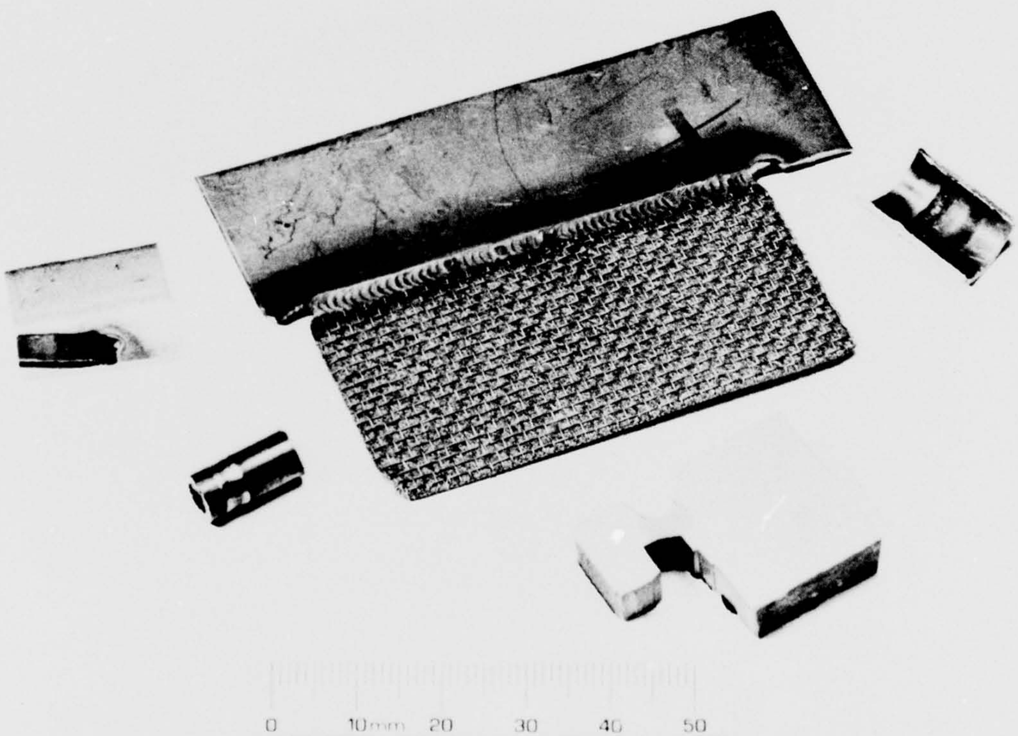


FIG. 4 Examples of various welded joints made with a transistorised power source.

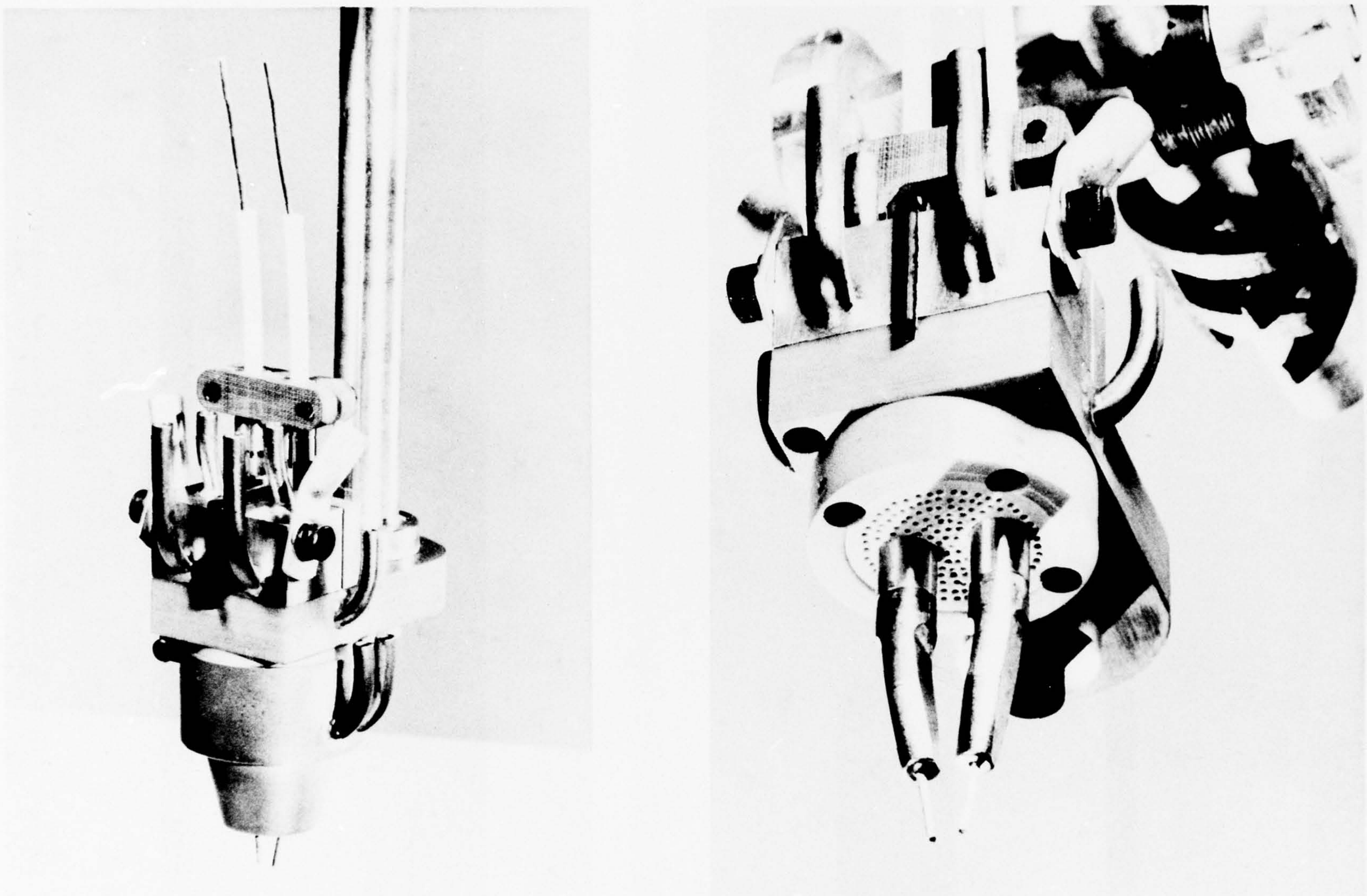
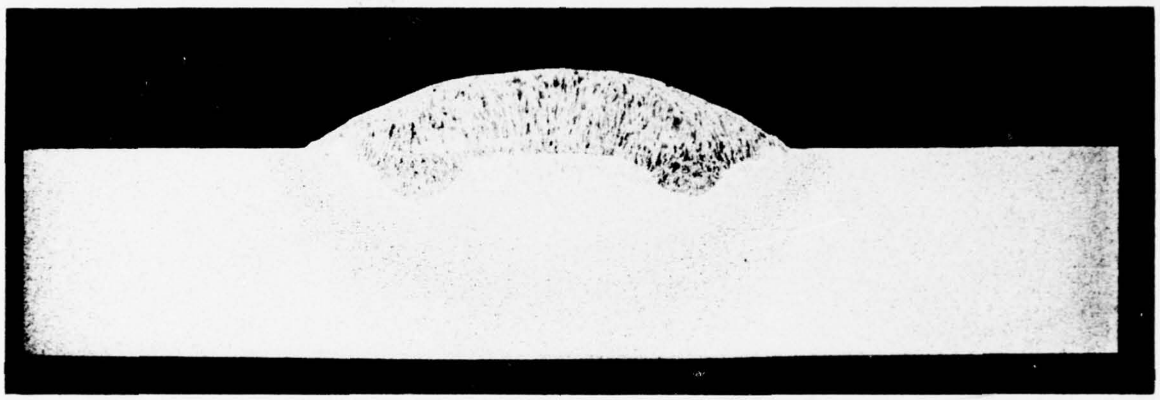


FIG. 5 Twin electrode MIG welding gun for mechanised tests:
(a) general arrangement, (b) view with gas nozzle removed.

(a)



(b)

(c)

FIG. 6 Effect of electrode separation on bead and penetration profile in switched MIG welding. Wire feed speed and travel speed constant. Electrode spacing: (a) 12.7mm, (b) 9mm, (c) 6mm. Total wire feed 5m/min (2.5m/min each wire). Total current 200A (100A each wire). Traverse speed 0.25m/min.

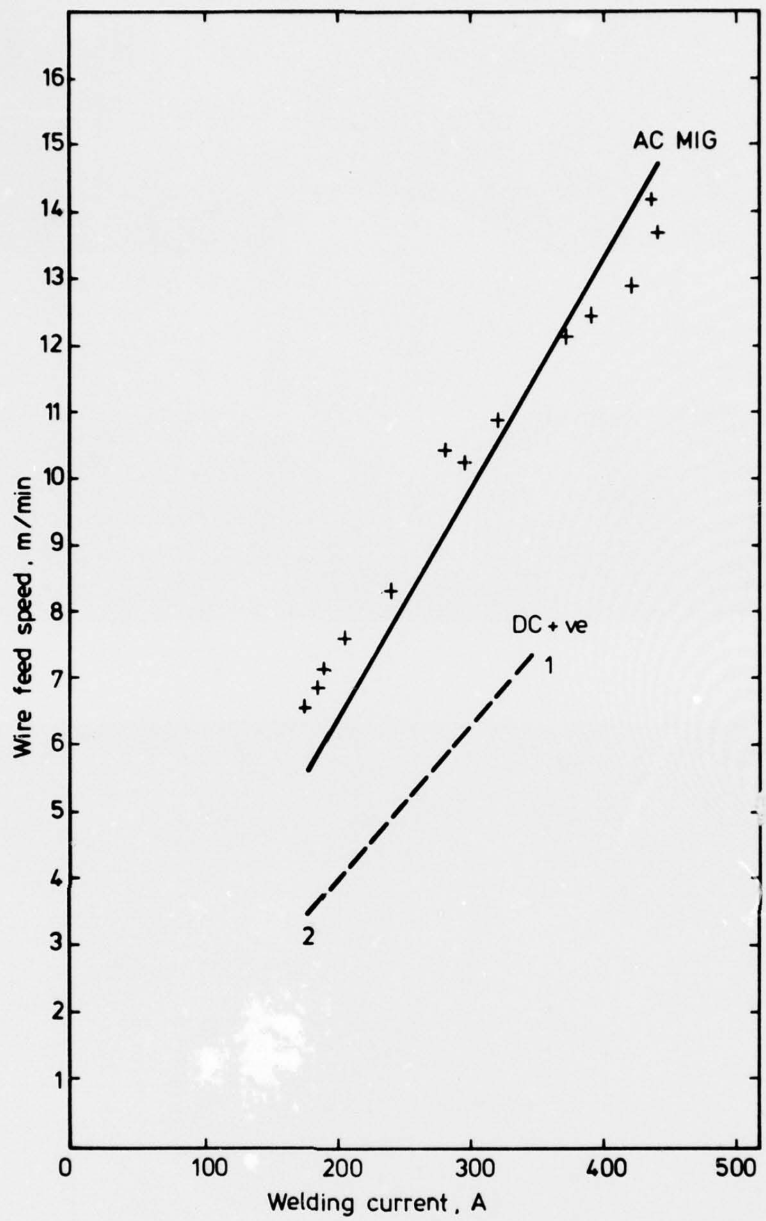
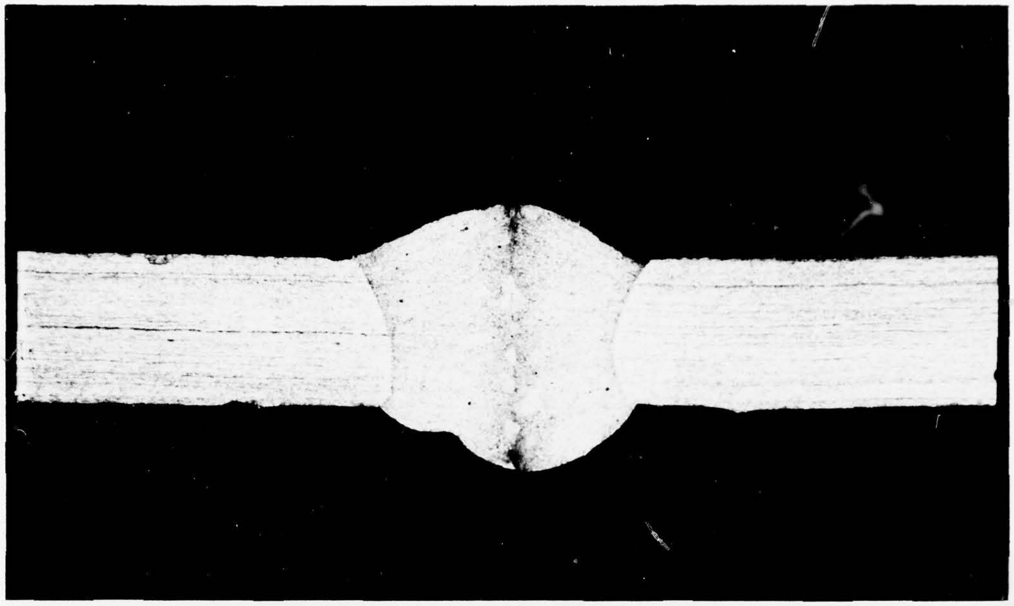


FIG. 7 Welding current/wire feed speed relationships for DC positive and AC welding showing extended working range and higher deposition rate of AC MIG. 1 - jetting and 2 - globular transfer regions (1.6mm aluminium wire).



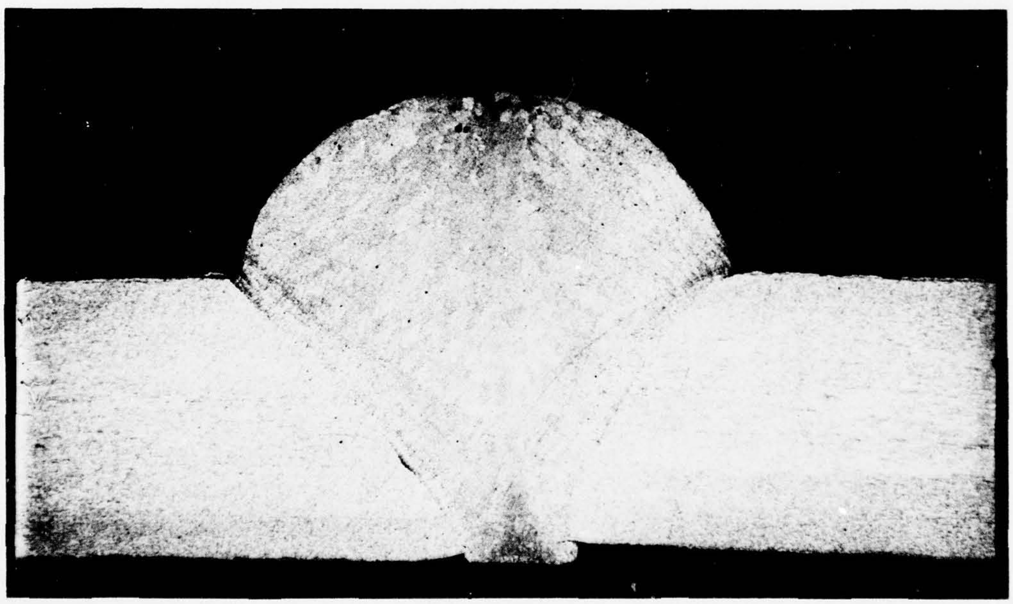
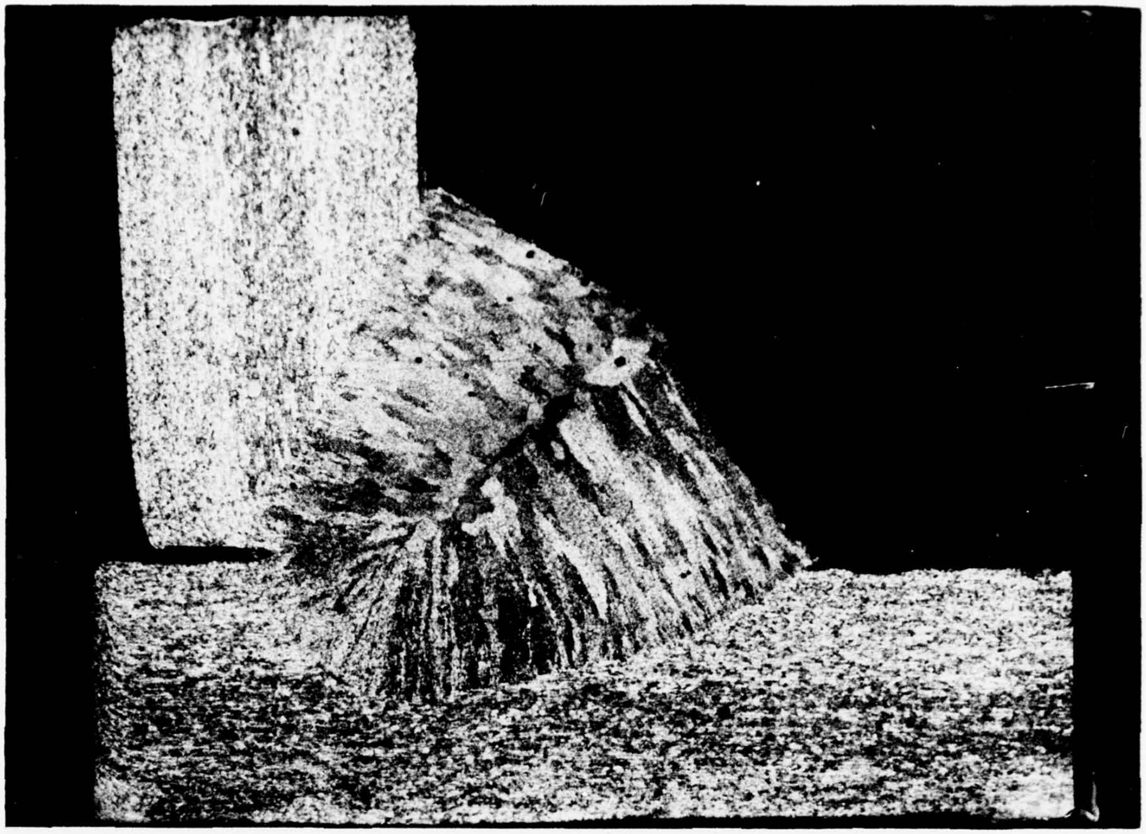


FIG. 8 AC MIG welding. Typical welded sections in various thicknesses of aluminium with joint preparation superimposed.



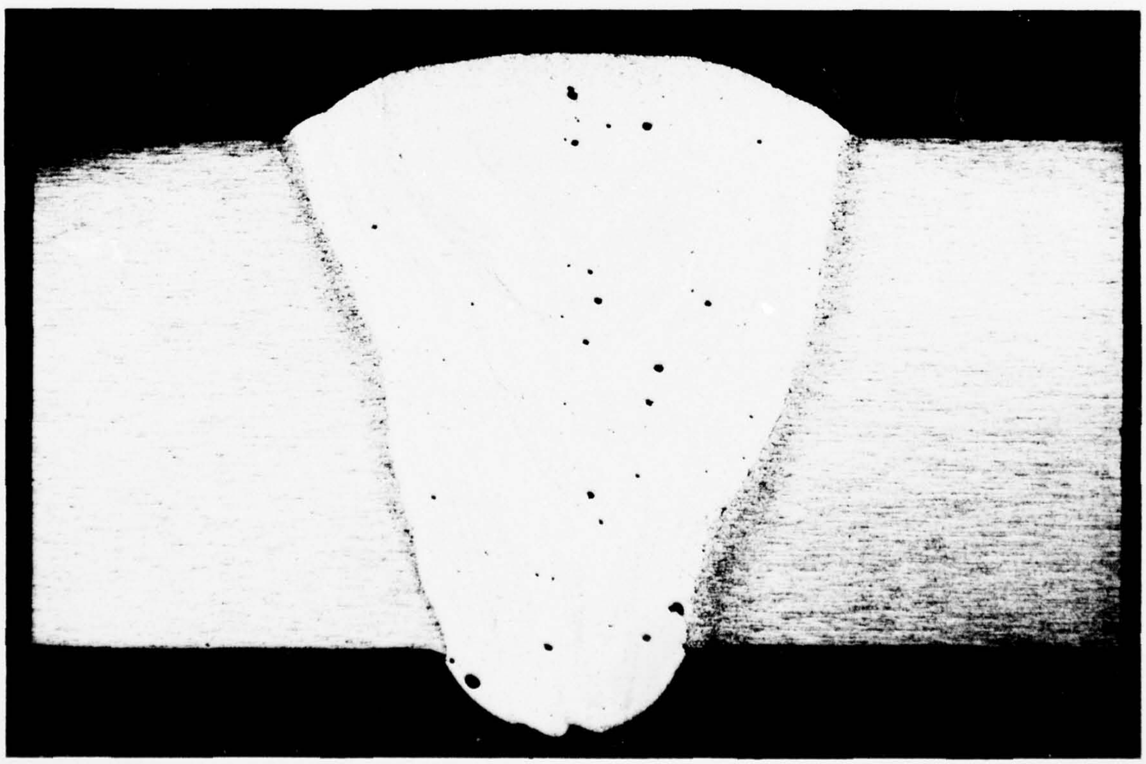


Figure 8 (continued)

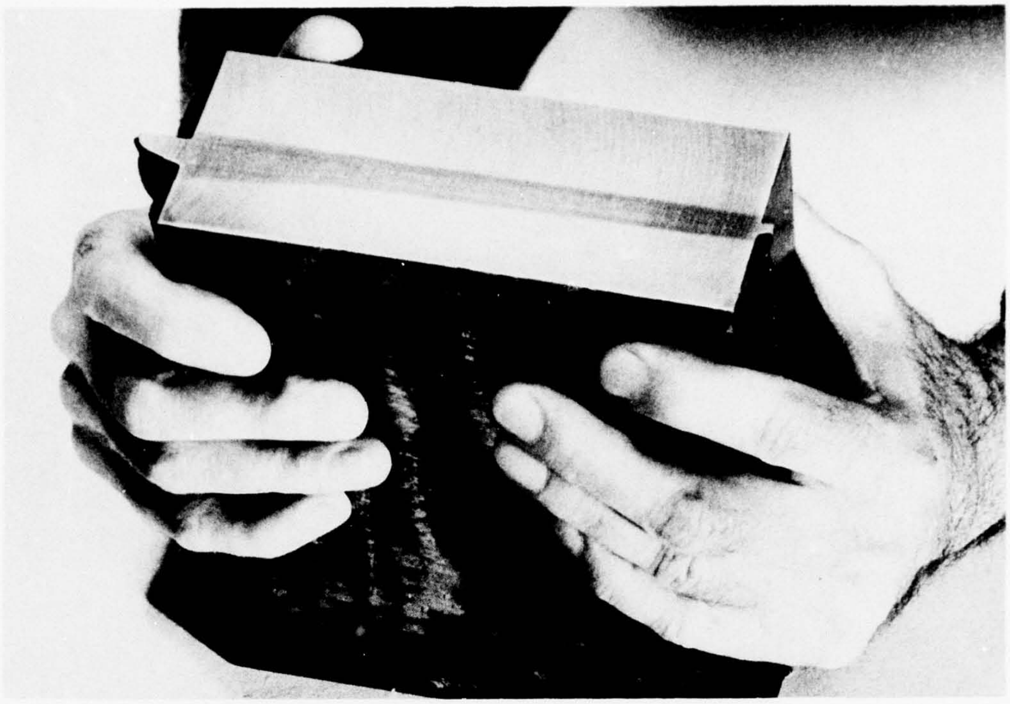


FIG. 9 Section of electron beam weld made in 150mm thick steel at 150mm/min travel speed.

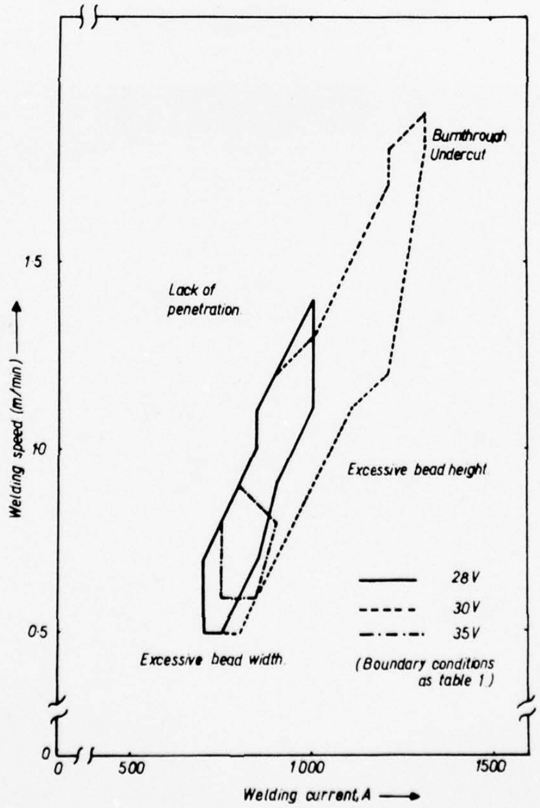


FIG. 10 Relation between welding speed and welding current in submerged arc welding at different voltages for DC electrode positive, 5mm diameter wire, 12.7mm thick steel plate, fused acid flux.

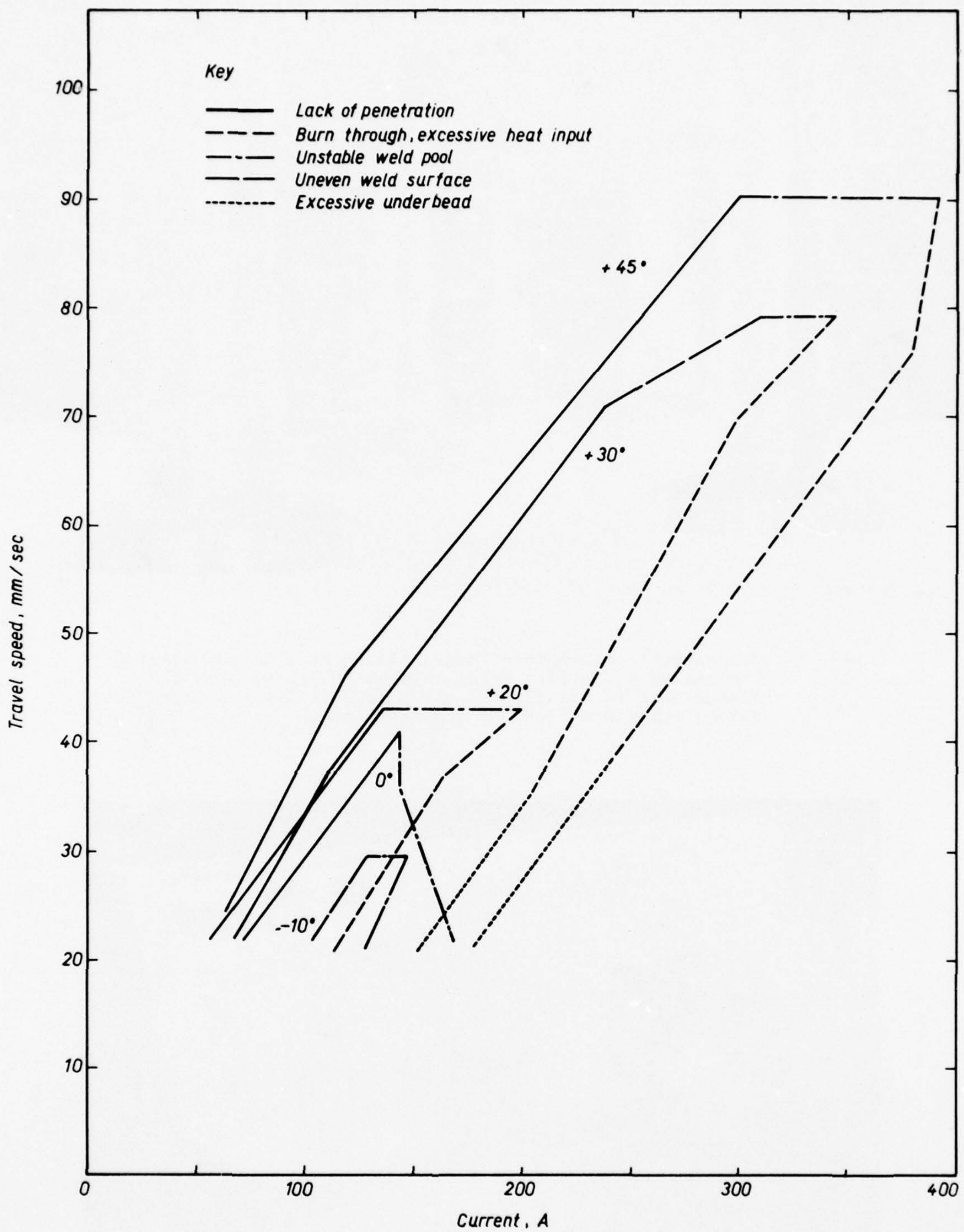


FIG. 11 TIG welding: Effect of electrode inclination on usable welding parameters for butt welds in 0.9mm stainless steel sheet.

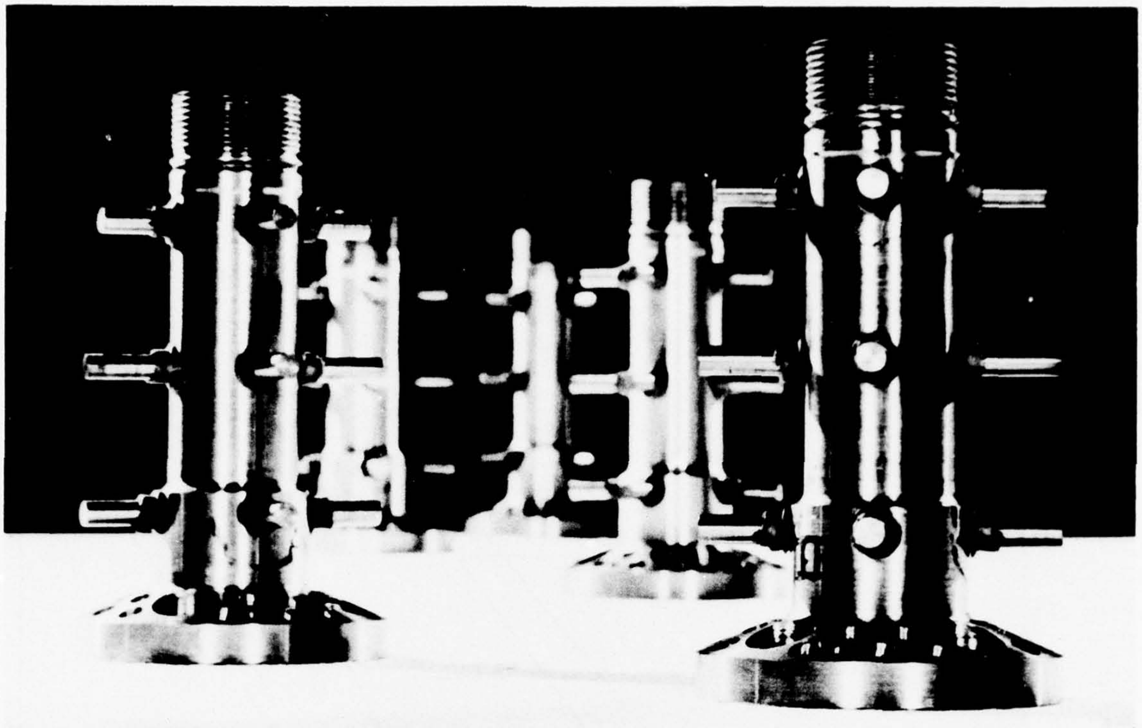


FIG. 12 High-precision component manufactured by friction welding. The twelve projecting studs have to be spaced with great precision both axially and circumferentially and there are narrow tolerances for the finished length.

FIG. 13 Special friction welder developed for manufacturing the component shown in Fig. 12.

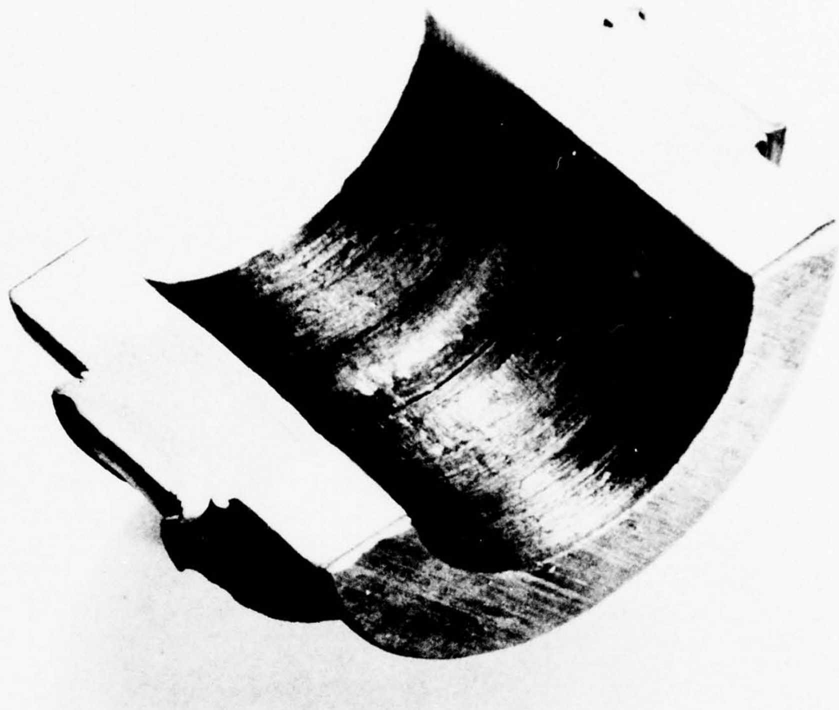


FIG. 14 Radial friction weld made in 4½ in. diameter tube.

NON-WELDING JOINING, CUTTING AND THERMAL SPRAYING METHODS

by

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SUMMARY

High mechanical properties under room and elevated temperatures significantly characterize high temperature brazed joints, provided optimum brazing conditions are maintained. Particularly in connection with nickel- and cobalt-base superalloys as parent materials this joining process reveals remarkable advantages.

No heat at all will necessarily be used in metal or polymer bonding, where no restrictions are given in the selection of material to be joined. The short term low temperature properties of the joints are excellent when thermal resistivity is poor, and long term properties, specially under environmental conditions, are widely unknown. However, many examples are known for applied bonding joints in aerospace industries.

Thermal cutting processes are used as preparation methods for metallic components prior to welding or other joining processes. Oxy-acetylene plasma arc and laser beam cutting offer certain advantages for particular materials and sheet thicknesses. There is a strong development in laser techniques by which cutting processes in aircraft industries will be affected.

Thermal spraying has turned out to be an efficient means for the protection of surface areas in structural aircraft components. Particularly in jet engines numerous parts are sprayed by flame, detonation or plasma process. Recent improvements in plasma spraying now offer sophisticated coating systems which even meet the requirements for highly loaded engine components such as turbine rotor blades.

1. INTRODUCTION

Beside welding, non-welding joining, cutting and thermal spraying techniques have gained place in aerospace technology. As far as joining is concerned, especial attention has to be given to high temperature brazing and bonding by plastic adhesives.

As compared with conventional welding techniques, the heat input in high temperature brazing is small, though gold, palladium and nickel- or cobalt-base alloys are used as filler materials.

High temperature brazing is preferably applied in airplane and turbine constructions when high temperature resistent Ni- and Co-base alloys are to be joined. As a result of investigations on the mechanical properties at low and elevated test temperatures, it is well established. It will be shown that high-temperature brazing turns out to be a promising means of joining high-temperature high-strength materials the welding of which is connected with serious difficulties.

Nearly all kinds of sandwich constructions can be produced by metal bonding provided the mechanical, physical and chemical properties of the adhesive meet the service requirements. Efforts have been made to improve adhesion and cohesion strength of the adhesive as well as its long term and environmental behaviour by means of reinforcements and the development and application of temperature resistent plastics.

As a preparation for welding and all other joining techniques, thermal cutting methods are widely used for aerospace components. Based on the present state of flame, plasma arc and laser beam cutting, we may predict that CO_2-laser beam cutting will rapidly develop into a potential means for cutting all kinds of materials with great efficiency. Increasing attention will certainly be paid in the future to applications and interesting metallurgical, technical and economic aspects as well as to special environmental problems.

Thermal spraying occupies a marginal place among welding techniques, though it has many uses including the production of coatings for wear and corrosion protection. For example, coatings are used for airplane turbine components by single and multi-layer spraying techniques. As established methods in aerospace industries, flame, flameshock and plasma arc spraying are applied in order to protect various components against elevated temperatures, wear, corrosion and erosion by special coating materials. Attention has to be given to the phenomena occurring in the adhesion of sprayed-on metal and non-metallic films to metal surfaces to their structure and properties as well as to possible means of quality control.

2. HIGH-TEMPERATURE BRAZING

2.1 INTRODUCTION

For the joining of high-strength materials, which are subjected to both elevated temperatures and higher mechanical stresses in service, an increasing attention is given to high-temperature brazing processes. Generally, the brazing procedure is carried out at temper-

atures between 900 and 1280 °C according to the kind of filler materials.

Brazing temperatures of the above degrees will obviously reduce the number of possible base materials to the high temperature range. Thus nickel- and cobalt-base superalloys and age hardening austenitic high-temperature resistant steels are preferably used as base metals.

Their field of application in aerospace industries is mainly that of turbine and engine manufacture, where high temperature resistivity up to 1200 °C is required / 1 /. The weldability of the materials mentioned above is limited, and structural changes - like those which occur in the HAZ during the welding - should be avoided in most cases. In this case high-temperature brazing offers a remarkable alternative to other competing welding methods. When different materials have to be joined, the welding properties of which vary, or when complex structures need joining processes, no difficulties arise in HT brazing owing to the manifold possibilities in operating procedures.

Brazing may be carried out both in vacuum or in a controlled atmosphere with no significant differences in the resultant properties of the joint. In the case of large structures, brazing is generally performed in an oven under controlled atmosphere and the heat treatment of the base metal components may follow the joining operation. On the other hand, electrical resistance or HF heated vacuum devices provide certain metallurgical advantages, because gaseous contaminations of the filler material as well as of the adjacent parent metals are minimized. Owing to the degassing effect of the vacuum, the oxygen and nitrogen contents of the liquid filler metal is reduced and easily volatilizing oxides of both filler and base metal constituents can disappear.

2.2 FILLER MATERIALS

Of the large variety of filler materials, which range from copper- and silver-base metals to nickel-, manganese-, cobalt-, gold- and palladium-alloys, those made from nickel and gold now offer the greatest advantages for aerospace application.

Because of their good resistance to high temperatures, nickel and cobalt provide a good starting point for development of filler metals for high-temperatures service, Table 1. The metals are sufficiently ductile. By proper additions of other elements filler metals are produced with excellent strength as well as oxidation and high temperature corrosion resistance. The elements commonly used as alloying additions are chromium, silicon, boron, phosphorus, iron and manganese. The primary function of chromium is to increase the oxidation resistance. The other elements increase strength, lower the melting point of nickel and promote wettability properties.

The alloying elements in the filler metals are necessary to obtain the proper brazing characteristics. However they show a strong tendency to aggressively corrode the parent metals. The corrosion takes place by diffusion into or erosion of the base metal.

Diffusion and erosion by nickel-base filler metals have been of particular concern to the aircraft industry where brazing of thin sections is a common practice. Although the nickel-chromium-boron and nickel-chromium-silicon filler metals are now widely used, the approval of the brazing alloys was slow. Owing to a lack of knowledge about the metallurgical changes caused by boron and silicon, very little was known about the characteristics of boron- and silicon-containing filler metals.

Several methods have been developed to minimize corrosion by brazing filler materials. The electroplating of the base metal by means of nickel has been found to prevent uncontrolled braze-metal/base-metal interface reactions / 2 /. Another means for minimizing this interaction is provided by accurate control of both the amount of filler metal and the brazing temperature cycle.

Another method is provided by the use of pure metal powders such as nickel or powders with the base-metal composition. The powders are added to the filler metal in order to inhibit the reaction with the base metal. Together with these precautions, the variation of the brazing alloy composition, the brazing temperature and the time at temperature are the important functions in the control of diffusion and erosion effects / 3 /.

The main applications of Ni- and Co-based brazing filler metal for high-temperature brazing are found in joining high-strength materials in turbine installations and aircraft machine engineering. High-temperature brazed joints provide excellent mechanical and thermal load carrying capacities as well as high-temperature resistance.

The required property of resistance to embrittlement at elevated temperatures is of particular significance for critical aircraft structures. However, when larger brazing gaps occur, the filler metals show strong sensitivity to embrittlement. In order to avoid the formation of brittle phases and the rapid diffusion of boron and silicon along the grain boundaries into the base material, the optimum brazing conditions have to be observed according to the prescriptions given by the producers of the filler materials.

2.3 PROPERTIES OF HIGH-TEMPERATURE BRAZED JOINTS

2.3.1 INFLUENCE OF THE HEAT TREATMENT ON MECHANICAL PROPERTIES

Among the various filler metals, the BNi-5 alloy has proved to provide excellent technical and economic performance when Ni-base alloys are to be joined.

The element Si, which decreases the melting range of the brazing filler metal BNi-5, forms silicide precipitations in the gap during brazing. Because of these silicides, low values of notch impact strength, fracture toughness, creep strength and fatigue can be expected. For the successful application of these joints, however, it is necessary to produce sufficient strength at high temperatures under static as well as under dynamic loading conditions. As shown in earlier investigations, the brittle phases in the braze control the progress of fracture / 4 /. Therefore attempts have been made to influence the structure of the brazed gap so that satisfactory values of toughness and strength can be achieved. The formation of gaps with not more than 15 µm in width eliminates the formation of silicides / 5 /. With respect to the ternary system Ni-Cr-Si, attention is drawn to the fact that the brazing filler metal BNi-5 is apt to form silicides.

Therefore, in gaps with a width not more than 25 µm, an interaction between base material and the brazing filler occurs and,as a result, the brittle phases disappear. By increasing the period for interaction of base material and brazing filler metal, it is possible to use a gap width of more than 25 µm and still achieve better structure. For example, the base material Nimonic 80A requires a solution heat treatment at a temperature of 1080 °C. It is possible to combine this solution heat treatment of the base material with the heat treatment to influence the formation of silicides. A temperature of 1100 °C for 20 hours was found to be a convenient heat treatment. In order to obtain optimum strength properties, the joints are age hardened at a temperature of 710 °C for 16 hours. This treatment causes a change in the microstructure as shown in Figs. 1 and 2 .

The influence of the heat treatment after brazing on the fatigue behaviour is remarkable, Fig. 3. The S-N curve shows a considerably increased strength under cyclic load at room temperature. If the brazed joint is subjected to a heat treatment at a temperature of 700 °C for a long period, the hardness of the braze decreases, but the age hardening raises the hardness of the base material, Fig. 4.

2.3.2 MECHANICAL BEHAVIOUR OF HIGH-TEMPERATURE BRAZED JOINTS

The mechanical behaviour of high-temperature brazed joints is determined by a large number of factors which exert influence on the materials, the geometry or the process. As to the materials, not only the properties of the high-temperature filler metals but also the mechanical qualities of the base materials determine the carrying capacity of the joints.

Under load a high yield strength of the parent metals generally prevents narrow gap joints from contracting in the joining area where a multiaxial stress condition is originated. By means of micro cinematographic examinations of joints made from the Nickel-base-superalloy NiCr20TiAl and the filler metal BAu-4, it was established that different sections of the joint participate in the failure process during loading / 6 /. During brazing the base material is subjected to temperatures exceeding that of the solution heat treatment. This may be the reason why the areas of the base material near the brazing seam tend to fail prematurely, Fig. 5.

The brazing seam, which occupies a width of about 100 µm, is situated between coarse grained base materials zones. Besides the plastic deformation of the filler metal, one can perceive the formation of first slip-bands in these areas. However the ductility remains poor.

In both the seam and the coarse grain areas the failure eventually takes place with the fracture following preferably the brazing seam with its inhomogeneous structure.

For practical applications the fatigue behaviour of joints in aerospace constructions is of considerable importance. A comparison of the fatigue strength for finite life of the NiCr20TiAl/BNi-5 joint at various test temperatures (room temperature and 700 °C) under one-stage as well as under multi-stage loading conditions is shown in Fig. 6. Investigations of the fracture surface of fatigue-loaded specimens showed that the crack mostly starts inside the brazed area and then extends through the cross section of the gap. The typical striation spacings were detected on the fatigue fracture surface, Fig. 7. They may easily be correlated to the cycles of the fatigue load during crack propagation across the examined area.

2.4 BRAZING DEFECTS AND THEIR ORIGIN

Most of the brazing defects refer to incorrect brazing temperatures. In general, four particular fracture types are discernable which are schematically represented in Fig. 8. In the case (a) a blow-hole exists the surface of which has a bright metallic aspect,Fig. 9. Figure (b) shows a plateau forming protrusions of considerable size.

The plateaus rise very abruptly from the surrounding surface. In this case the fracture surface lies in the brazed seam, whereas in figure (c) the fracture is at the base material,

i.e. on the braze interface. The surrounding surfaces of these fractures are frequently oxidized. Grinding marks can be discerned. It is assumed that insufficient bonding during the brazing process occurs and that post-brazing heat treatment gives rise to oxidisation. A failure as a result of adverse surface tension effects in shown in figure (d).

As these defects may considerably reduce the life of important structural components, great care should be given to the accurate observation of optimum brazing conditions.

3. ADHESIVE BONDING

3.1 INTRODUCTION

Besides riveting and bolting, adhesive bonding appears to be the only possibility for joining a large number of materials.

The systematic development specially of metal bonding techniques was initiated by the aircraft industries owing to the numerous advantages offered to cell structure designers.

In contrast with welding or brazing, bonding does not need elevated temperatures so that neither structure nor mechanical properties of the materials are influenced detrimentally.

Modern adhesives are made from synthetic polymers with a relative low strength as compared with metals. Therefore, bonded structures normally require large joining areas and are used in single or double overlappings.

In these bonds stress concentrations, which occur in spot-welded or riveted joints and have led in the past to severe failures, are avoided, Fig. 10.

Furthermore, bonded structures do not only reveal a nearly ideal stress distribution but also prevent moisture from penetrating into overlapped joints, thus providing a good corrosion protection.

One of the most important advantages of bonding is the fact that all materials can be joined together, thus enabling hybrid-, sandwich-, or reinforced structures, Fig. 11. The main problems in bonding technology derive from the low thermal stability of the adhesives. Generally, plastic adhesives must not be applied at temperatures above 80 to 100 °C. Recent developments of aromatic polymers as polysulfons, polyimides, or polybenzimidazols remarkably improve the ability of adhesives to resist higher temperatures up to about 400 °C. However, with the rise in temperature the cohesive strength decreases and the adhesives suffer from creeping under long term loading conditions.

The thermal resistivity of special ceramic adhesives now increases up to 1000 °C provided moisture does not penetrate into joining area.

Another problem of bonding consists in the low adhesion of polymer adhesives to certain materials and therefore complicated surface pretreatments are required.

After all, there is a problem which results from the little experience in joining by means of adhesives. Particularly few tests have been made in respect of the mechanical long-term behaviour, specially under environmental conditions. Many results providing basic experience have been achieved in the short-term range, whereas no prediction of long-term properties can at present be made. The possibilities for non-destructive testing of adhesive joints are still rather poor.

3.2 BONDING PROCESSES

Adhesion is based on the sorption phenomenon of plastic molecules on solids initiating physical and chemical bond mechanisms / 7 /. There is no interaction with the joined component neither of the dissolvent nor of glue constituents.

In metal bonding, only a physical adhesion of the glue takes place. In bonding of polymers both adhesion and diffusion processes are possible / 8 /. Diffusion of adhesive constituents or of dissolvents quite often initiates stress cracking in many polymers. Therefore, the pure adhesion bonding is of particular interest for bonding polymers. However, a good adhesion on polymers normally requires an expensive pretreatment of the surfaces. Furthermore, the mechanical long-term behaviour often remains insufficient / 9 /. Thus diffusion bonding for joining thermoplastic polymers is preferred in many cases / 10 /.

Beside a good adhesion, the harmonization between the ductility of the adhesive and that of the joined material influences the mechanical behaviour of the glued joint. Most of the polymers are well deformable materials. If they are combined with stiff glues, this will inevitably lead to stress concentrations at the ends of the overlap bond. Therefore, pure epoxy- or phenolic resins are not applicable for joining purposes. They must be modified by thermoplastic components. Thus they are able to equalize stress concentrations by creep processes. In order to minimize the creeping, modern adhesives are reinforced by polymeric fibers.

Bonded joint loadability generally is based on the conditions of adhesion and deformation. Furthermore, certain joints possess anchoring points of the adhesive in grooves on the surface which improves the mechanical properties. In light constructions this effect appears to be important. E.g. in a sandwich the inner component consists of a porous material such as

wood or polymeric foam.

In metal bonds the quality of adhesion may influence the shear strength. Roughening of the surface has a cleaning effect and increases the active surface. But there is no improvement of bond strength caused by mechanical interlocking.

The small active range of the adhesion energies requires a good wetting of the surfaces by the adhesive, which is achieved by decreasing the viscosity of the adhesive and increasing the surface tension of the solid / 11 /.

For this reason the surfaces should always be carefully cleaned.

In the case of steel bonds, sandblasting and degreasing of the surfaces are necessary because degreasing alone causes sensitivity to corrosion / 12 /, Fig. 12. Sandblasting and degreasing also is the optimum surface pretreatment for reinforced plastics. This material is more and more used for aircraft structures. It contains either glass-, carbon- or boron fibre reinforcements, Fig. 13. The shear strength of the bonded structure will generally exceed the interlaminar shear strength of the reinforced plastic / 13 /.

As matrix for the reinforcement, polyester-, epoxy- or polyimid resins are employed which are bonded in the best way by modified epoxy resins. For steel bonds additionally modified phenolic resins are suitable.

Mechanical pretreatment has turned out to be insufficient for some metals and polymers owing to their anti-adhesive surface properties. There are aluminium and titanium alloys and polymers like polyolefines, fluorinated polyolefines and silicon resins. These polymers are widely used in aerospace industry owing to their extraordinarily good chemical and thermal resistance, specially at low temperatures. They need a chemical pretreatment with chromic acids or liquid alkali metals in order to be joined by adhesives / 10 /.

Like these polymeres, aluminium and titanium alloys require a chemical pretreatment for a good adhesion. In the case of aluminum alloys, pickling with chromic acids followed by an anodizing process has proved to be the most recommendable pretreatment / 14 /.

As shear strength and aging resistance depend on both the pretreatment and the adhesive, the best combination for every new adhesive has to be examined.

The mostly approved chemical surface preparation for titanium alloys is by hydrochloric or hydrofluoric acids which improve shear- and peel strength of the bonds, Fig. 14.

3.4 MECHANICAL BEHAVIOUR

A difficult problem of bonding arises from the great number of parameters influencing the mechanical properties of the joint. Several methods have been developed to make predictions of the bond quality possible by measuring surface properties such as tension, electron emission, sorption and desorption of the resins by radiation measurements / 12 /. These methods provide a quality control of surface preparation, but they do not give any information about the shear- or peel strength of the bonded structure.

The mechanical behaviour of a bonded joint does not only depend on the adhesive power but also on the joint configuration, thickness, cohesive and deformation properties and on the environmental behaviour of the components. Owing to the influence of geometry, test results abtained from small specimens cannot always meaningly be applied to constructions. Mathematical solutions for a correlation of specimen and construction geometries are only possible in very simple structures / 15 /.

In many other cases tests of the complete construction under actual conditions are inevitable.

In addition to long-term and environmental sensitivity, chemical bonds, specially those of aluminum, are not water-resisting at the interface for a long time / 16 /.

The most important result recently obtained from aging tests have proved that aging processes are accelerated under load conditions.

3.5 APPLICATION

The most suitable adhesives for metal bonds in aircraft structures under environmental conditions are still based on phenolic resins, but epoxy resins reveal nearly the same good results / 12 /.

Classical examples for bonded structures have been incorporated in the aeroplanes F 27 and F 28 manufactured by Fokker of the Netherlands. In these aircrafts more than 400 components have been bonded by adhesives. Besides the technical advantages Fokker has obtained economic benefit by lower production costs and lower weigth. Thus the freight capacity has been increased as an additional result.

In the planes transverse bulkheads, frames, stiffening sections, service gates, steering blades and blade borders have been bonded by means of Redux 775 which is a modi-

fied phenolic resin (Fig. 15). Only a few ends of stringers or sections have also been riveted in order to cross the peel tension.

The joining of parts with the use of adhesive bonding and mechanical fasteners or spot welding methods has come into praxis in aerospace manufacture.

For a while fasteners seemed to be superfluous in the light of development of high strength adhesives. Tests / 17 /, however, have proved the superior strength of weld-bonded joints. The weld bond process uses resistance welding together with adhesive bonding. Most of the work performed up to now has been based on resistance spot welding through the adhesive. This method has been applied in the construction of the supersonic Russian aircraft TU 144.

Adhesive bonding enables the combination of different materials in one structure, so that high strength materials can be used together with extremely light ones, for instance in honey comb structures (Fig. 16). Other possible combinations consist in materials with extremely good electrical or thermal conductivity and insulating materials, for instance in solar cells (Fig. 17).

By the rolling of metal sheets, constructions may be built up from sheet with changing cross sections without any excess of metal. Expensive production methods, which are at present applied in the manufacture of the MRCA/Tornado aircraft with cutting rates of 90 %, will no longer be required if all bonding problems are solved.

4. THERMAL CUTTING

4.1 INTRODUCTION

Thermal cutting covers various processes which have in common that the cutting proceeds along an outline where a kerf is produced by ejecting the liquid, oxidized or volatilized material from it at a high temperature. The cutting processes mostly used in aerospace industries are oxyacetylene, plasma arc and laser beam cutting.

The structural parts manufactured in aerospace industries are made from steel as well as from aluminum, titanium and their alloys, nickel-cobalt-base superalloys and non-metals. Furthermore, different thicknesses are applied, and more than one thermal cutting process is necessary to meet the requirements for a preparation method, for welding and other joining techniques. On the one hand, the requirements consist of a sufficient economy in comparison with the various mechanical cutting methods. On the other hand, the call for maximum cutting speeds must not be connected with a low level of accuracy. Modern thermal cutting plants exhibit high cutting speeds and a high level of accuracy provided the most suitable process is applied. Additionally, a high standard of process control is reached with the available control systems ranging from tracing by magnetic roller head and photoelectric scanning of drawings to computer numerical control.

4.2 PROCEDURES AND APPLICATIONS

In oxy-acetylene cutting, the application of the process is limited to those materials which immediately form oxides with melting points well below that of the metal itself. As a consequence, only a small number of alloyed steels can be cut without preheating / 18 /. However, the cut edges will definitely harden, even if mild steel is cut. The hardening effect is accompained by the formation of residual stresses which may be of both tension or compression (Fig. 18). The kind of residual stress, its level and its changes from the cut edge to the interior largely depend on the material to be cut and on the process employed, including the numerous variables involved. Higher alloyed steels need a preheating of about 200 ^{o}C. Others cannot be cut by the oxy-acetylene torch at all. Among them are a lot of aircraft materials. Aluminum and titanium alloys also require other cutting processes.

However, good results have been obtained by oxy-acetylene cutting of 1 % Cr, 0.3 % Mo-steel similar to the British BS 3100/1456 and the American AMS 5335A grades. The HAZ has remained small as compared to plasma arc cutting of the same steel sheet. There has been no evidence of remarkable deviations from the parallelism of the walls that can often be observed at plasma arc cuts / 19 /. Thus the oxy-acetylene flame cutting process offers not only economic but also technical advantages provided it is applicable.

The application of the plasma arc cutting process is not limited by the chemical composition of steels. The thickness range for this procedure extends from about 3 mm up to about 150 mm for metallic materials irrespective of the kind of metal or alloy.

Plasma arc cutting is a transferred arc process. It can be hand-operated or mechanized. Hand-operated installations use argon/hydrogen gas mixtures, whereas mechanized installations additionally employ nitrogen, nitrogen/hydrogen or nitrogen/oxygen gas mixes. Cutting speeds can be up to ten times faster than oxy-fuel gas cutting. The cuts often do not require machining or further finishing.

Investigations on a 10 % Ni-steel resulted in an overall superiority of plasma to oxy-fuel cutting; however, higher hardnesses have occurred at the cut edges, and the walls deviated from the parallel shape / 20 /. In recent years high-quality cutting torches have been developed which achieve cut surfaces characterized by sharp top and bottom edges, parallel

walls and only slightly attached or completely absentdross on the bottom of the cut. These devices use multi-port plasma arc cutting nozzles providing narrower kerfs owing to the fact that the arc is shaped beyond the nozzle. Other devices produce a secondary gas shield of CO_2 or compressed air, thus changing surface tension and viscosity of the melt and permitting considerably higher cutting speeds and smoother walls. Fig. 19 shows schematically a dual-flow plasma torch.

Another method to improve cut quality and to avoid fume formation and air pollution consists in injecting water into the plasma (water injection plasma arc cutting) or in performing the whole cutting procedure under water (Fig. 20). Thus the gases developing during the cutting operation may quickly dissolve in the water, whereas the liquid metal of the work piece forms droplets sinking to the bottom of the water tank. Noise will be lowered by approximately 15 dB, and the intensity of the UV-radiation is considerably reduced. Furthermore, the sheets remain cool so that distortion effects are avoided. Thus not only technical improvements are achieved, but the process remarkably contributes to the reduction of environmental problems during plasma arc cutting. This is of even greater importance when nickel or nickel-base alloys are plasma cut, because the produced nickel-containing fumes are highly toxic and may cause cancer.

Another energy source for cutting is used in laser beam cutting. In contrast with the oxy-fuel and plasma arc method, the material of the workpiece is not heated by convection by means of a flame or an arc, but by absorption of radiation energy. The monochromatic and nearly parallel light beam issues from the device and is focussed to the workpiece by an optical system. Supported by a jet flow issuing from the laser head together with the laser beam, the output from the lasering CO_2-system volatilizes the material. In the case of flamable materials or for non-oxidizing cutting, the gas jet consists of an inert gas blowing the molten part out of the kerf (Fig. 21). When oxygen is used as an alternative, the metal oxidizes more rapidly than in oxy-fuel cutting (Fig. 22).

At present laser devices applied in various industrial branches offer outputs of about 0,3 kW, which is enough to cut sheets of up to 3 mm, high-alloyed steel or 0.2 mm Al. With the same equipment, non-metals up to 12 mm or titanium more than 10 mm in thickness can be cut. Ti-plates of over 40 mm in thickness can be cut when oxygen is used as a cutting gas.

In aerospace industries laser beam cutting is widely used for the manufacture of sheet parts made from Ti or Ti-alloys or Ti-coated composite plates. Processing measures by electronic steering with capacitive tensors provide facilities for easy cutting of structural parts of complicated shapes.

Owing to the strongly reflecting surface together with the high thermal conductivity, aluminum creates difficulties in laser beam cutting. Recently, however, progress has been made allowing the cutting of Al-sheets of 3 mm in thickness by means of a 900 W-CO_2-laser. The development of CW-high-power-CO_2-laser will certainly reveal a wider range of applicability in many industrial branches for cutting as well as for welding.

5. THERMAL SPRAYING

5.1 INTRODUCTION

Thermal spraying is based on methods by which a metallic or nonmetallic wire or powder is melted. The fused particles are projected on to a prepared surface so as to build up an adherent coating which has to serve as a means for corrosion protection or wear resistance such as heat or air barriers and for repairing components.

The thermal energy necessary to melt the spraying material can be produced in different ways. Flame and plasma spraying as well as detonation plating are at present the mostly applied thermal spray procedures in aerospace industries. Particularly plasma spray deposition has been developed as a practicable processing technique for the last ten years.

E.g. by the use of thermally sprayed coatings the life of aircraft jet engines has successfully been extended. Thus one of the major problems facing the airline industry has partially been solved, namely the wear of non-lubricated mating parts of mechanical components resulting from vibration, fretting, impact and hammer wear during engine operation. In other areas of a jet engine, ceramic/metallic thermal barrier coatings are used in order to reduce metal operating temperatures and the effects of thermal transients on combustion chambers. The latest application of high-power plasma spraying is to provide coatings for turbine blades by using a transferred arc and high particle velocities.

The significance of thermal spray processes may be proved by the fact that a single engine may employ as many as 600 coated parts. It must be admitted that spray deposits have sometimes fallen into disrepute as a result of incorrect applications. Therefore, the very efficient spray techniques should be used only when they offer advantages and never when other techniques are better.

5.2 METHODS

Flame-, plasma- and detonation spraying are widely employed in the aircraft industry (Fig. 23). In flame-spraying the consumable wire or powder is fused by a oxy-acetylene flame (Fig. 24).

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Electric arc spraying is applied too, but much less as compared to other processes. Arc spraying on the free atmosphere using compressed air as propellant gas is not used in practice to establish coatings in air-craft and aero-space industry. A promising development for arc-spraying of metals with high affinity to oxygen or nitrogen has been brought about by introducing shielding gas chambers, Fig. 25. By spraying in a controlled atmosphere, oxydation resulting from the conventional open-air-spray process can completely be avoided. By selecting adequate shield gas composition, the properties of the coatings can by varied within a wide range. Thus it has been possible to establish hardness values of 250 HV 0.1 to 1100 HV 0.1 on sprayed titanium.

By detonation spraying extremely dense coatings with a high bond strength to the substrate can be produced. As shown in Fig. 26, the energy to accelerate and heat the particles is taken from a oxy-fuel combustion in a detonation pipe. The disadvantage of the process is the high cost which limits its application to high loaded parts.

Plasma spraying is the mostly employed method of thermal spraying in aero-space industry. In conventional plasma spraying, a non-transferred arc is used as energy source. The arc is struck between a tungsten cathode and a water-cooled copper anode. The ionised plasma gas is constricted when retiring from the nozzle with a high energy and enthalpy and forms a torch. In accordance with the material to be sprayed, nitrogen/hydrogen, argon/hydrogen or argon/helium mixes are used as plasma gases. The powder material is fed into the plasma stream where it is melted and accelerated to high velocities, (Fig. 27). Owing to the enormous heat available all materials such as tungsten, carbides, oxides and other high melting materials can easily be melted and sprayed. Conventional plasma spraying allows to establish well bonded coatings with a density of 85 % up to 98 %.

The demands for higher bond strengths and homogeneous coatings have led to the development of high power plasma spraying. The power has usually been increased to 80 kW and in some cases to 200 kW. However, the particles are exposed to the plasma gas for a very short time. Though improved coatings can be produced, the excellent quality of detonation gun coatings is not achieved.

Another important development provides high power plasma spraying with transferred arc inside a vacuum container. As a result uniform coatings with high bond strength and good homogeneity tend to become competitors to those produced by detonation spraying.

The equipment for high-power-vacuum spraying with transferred arc is shown in Fig. 28. Plasma velocities of Mach 2 to 3 give rise to high densities of 96 to 99 per cent of theoretical values. Bond strengths in excess of 14 kgf/mm^2 with both metal and ceramic coatings can be achieved / 21 /. The superimposed transferred arc is separately controlled and produces coatings of impervious nature and fusion bonding / 21 /.

This technology is of major interest particularly in the aircraft industry and specially in the manufacturing of turbine blades. Fig. 29 shows the plasma stream with the superimposed transferred arc and a turbine blade to be sprayed under low pressure conditions.

5.3 SPRAY MATERIALS AND APPLICATIONS

The materials used in aircrafts range from stainless steels to high temperature nickel and cobalt base alloys. The largest use of plasma spray coatings has been limited to engine parts. Such coatings are used primarily as thermal barrier, wear, galling and erosion resistance and for dimensional restoration / 22 /.

Wear of non-lubricated engine parts and the high temperatures existing in the combustion chambers are the chief problems of the aircraft in respect of long life. Sprayed coatings are able to reduce the wear resulting from vibration, fretting and impact during operation as well as the heat influence on the construction materials.

The environmental and mechanical loading conditions have to be considered, in selecting the suitable spray materials. Several ceramic/metallic thermal barrier coating systems based on magnesiastabilized zirconium oxide have been successfully applied over the past ten years to sheet metal components in several gas turbine engine models / 23 /. Furthermore aluminum oxide and pure zirconium oxide are used as thermal barriers. Ceramic coatings tend to spall under thermal cycling. In the case of magnesium zirconate this drawback is overcome by applying a bond coat of Ni-Al coating followed by an intermediate layer composed of a mixture of Ni-Al and magnesium zirconate. The intermediate coating has a coefficient of expansion between those of Ni-Al and magnesium zirconate / 22 /. The requirements for greater combustion chambers and turbine duct component cooling without giving up engine efficiency had led to the development of the continuously graded thermal barrier coatings / 23 /. These graded coatings exhibit good substrate bonding and intercoating integrity even at high temperatures as compared to the multilayer (as a rule: three layer)coating systems which often spall within one or more of their coating layers, whereas thermal barrier coating system based on Ni-Al or Ni-Cr metallic components have shown good service in a number of applications. When failures have occured, they have been found to have been caused by oxidation and degradation of the metallic constituent followed by exfoliation of the outer ceramic or intermediate transition layer / 23 /.

Laboratory static oxidation testing of continuously graded CoCrAlY-magnesium-zirconate on Hastelloy X test panels have shown a significant improvement as compared to the nickel-

chromium based system at 980 °C test temperature / 23 /. The nickel-chromium component in the graded portion of the coating was fully oxidized after 200 hours exposure, whereas the CoCrAlY component showed small oxidation effects / 23 /.

The selection of wear resistant spray materials depends on the environmental conditions, specially temperature and mechanical loading. For operating temperatures up to 537 °C, tungsten carbide base coatings have revealed optimum performance under given conditions. For operating temperatures above 537 °C chromium carbide in addition to cobalt base coatings have been found to be most useful. These materials are used for applications at temperatures in the 537 °C to 980 °C range / 24 /. Powder mixtures of 15 % Ni and 85 % $WTiC_2$ and 25 % NiCr and 75 % Cr_3C_2 are also successfully employed at temperatures above 500 °C. In the case of the last mentioned powder, a core existing of Cr_3C_2 is enveloped by a Ni-Cr layer / 25 /.

Sprayed coatings are also used as abradable seals / 22 /. Materials such as Ni-Al composite powder or Nickel-Graphite (75 % Ni/25 % C) have been sprayed to produce satisfactory coatings as abradable seals. These materials tend to give better coatings by flame spraying than by plasma spraying because of the lower density attained by the former process / 22 /.

A thermal barrier coating applied to an inner combustion chamber of a large turbine has been shown in Fig. 30. The microstructure of the coating has been shown in Fig. 31.

In order to increase the efficiency of the engines, the clearance between rotating blades and stationary casing has to be minimized. Casings are lined with abradable seals that would abrade or wear away during the early blade rotation and thus conform to suitable contours, (Fig. 32). The materials used for abradable seals have been shown in Fig. 33.

As mentioned above, dense and well bonded coatings can be manufactured by making use of the vacuum plasma spray process. Fig. 34 shows the microstructure of a hot corrosion resistant coating (CoCrAlY) sprayed with transferred arc in a vacuum chamber (0,05 bar) without post heat treatment, see Fig. 35 after diffusion heat treatment. As has been shown in Fig. 34, the coating is uniform, free of inclusions and absolutely dense. After diffusion treatment a texture is formed which consists of a fine Co-Al-segregation and a solid solution with a high Co-content. The turbine blade shown in Fig. 36 is coated with such a hot corrosion resistant CoCrAlY-alloy.

An example of a thermal barrier coating has been given in Fig. 37, which shows a turbine housing of a rocket engine with a ZrO_2-coated tube / 25 /.

Plasma spraying of areas subjected to wear in an aircraft includes a big field of application. The inside bores of hydraulic cylinders are sprayed with wear resistant coatings as well as the non-lubricated areas in the jet engines.

Sometimes the properties of the coatings sprayed both by conventional and high power plasma spraying are not adequate. Fig. 38 shows the microstructure of a wear resistant WC-Co coating. The texture is both homogeneous and free of inclusions / 26 /.

5.4 QUALITY CONTROL

Quality in sprayed coatings stems from good process control at every stage of the processing cycle / 27 /. A variety of tests is used to establish the quality of a deposit. When destructive tests are used, they should be performed on test pieces. The problem is to ensure that the spraying conditions used on the component are substantially the same as those of the test coupon / 27 /. Suitable destructive tests are metallographic examinations, hardness tests and estimation of coating adhesion and tensile strength. At present non-destructive test methods are not available owing to the inhomogeneous structure of the coatings. However, interesting development has started with the use of Rayleigh waves / 28 /. Pulses are injected into the substrate by the transmitter probe and travel substantially beneath the coating. In accordance with the extent and quality of the bond, the pulses may more or less penetrate into the deposit where they suffer attenuation. The residual signal is detected by a probe beyond the coating. The degree of attenuation can be related to the bond strength.

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Table 1: Brazing filler metal

Base of filler metal	Specifications			Chemical composition (Weight %)												melt. range	
	AWS	AMS	Firms	Ni	Cr	Si	B	P	C	Co	Au	Pd	Mn	W	Fe	sol.	liqu,
Ni	BNi-1	4775A	NB125	Bal.	13-15	4-5	2,75-3,5	<0,02	0,6-0,9	-	-	-	-	-	4,5	980	1060
Ni	BNi-2	4777	L.M.	Bal.	6-8	4-5	2,75-3,5	<0,5	<0,06	-	-	-	-	-	2,5 bis 3,5	970	1000
Ni	BNi-5	4782	NB30	Bal.	18,5 - 19,5	9,75 10,5	<0,03	< 0,02	<0,1	-	-	-	-	-	-	1080	1135
Ni	BNi-7	-	NB50	Bal.	13-15	<0,1	<0,01	9,7- 10,5	9,7- 10,5	-	-	-	-	-	<0,2	890	890
Ni	-	-	NB150	Bal.	13,5 - 16,5	-	3,25-4	< 0,02	<0,1	-	-	-	-	-	<1,5	1055	1055
Ni	-	-	Nb170	Bal.	10-13	3-4	2-3	< 0,02	0,4- 0,55	-	-	-	-	15- 17	2,5 bis 4,5	970	1105
Co	BCo-1	4783	NB210	16-18	18-20	7,5- 8,5	0,7-0,9	< 0,02	0,35- 0,45	Bal.	-	-	-	3,5 4,5	-	1120	1150
Au-Ni	BAu-4	-	VH950	18	-	-	-	-	-	-	82	-	-	-	-	950	950
Au-Ni-Cr	-	-	Cromico	22	6	-	-	-	-	-	72	-	-	-	-	980	1040
Ni-Mn-Pd	-	-	NMP1	48	-	-	-	-	-	-	-	21	31	-	-	1120	1120
Pd-Ni	-	-	-	30	-	-	-	-	-	-	-	60	-	-	-	1237	1237
Mn-Ni	-	-	-	30	-	-	-	-	-	-	-	-	70	-	-	1000	1020

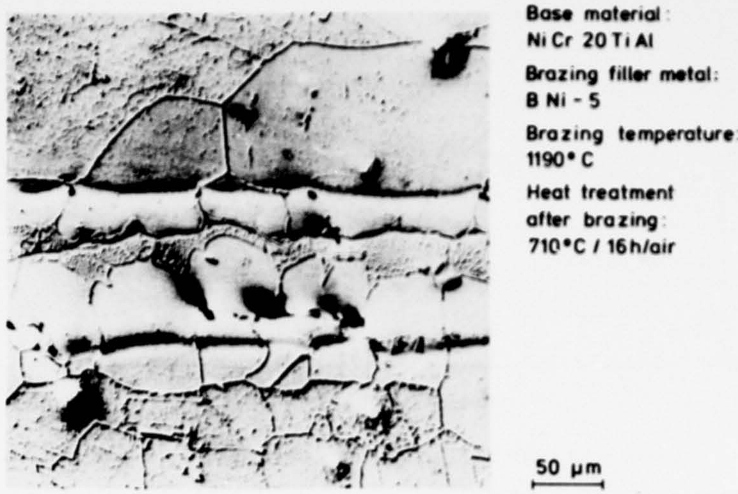


Fig. 1 NiCr20TiAl/BNi-5 brazed joint, heat treatment after brazing: 710 °C/16h/air

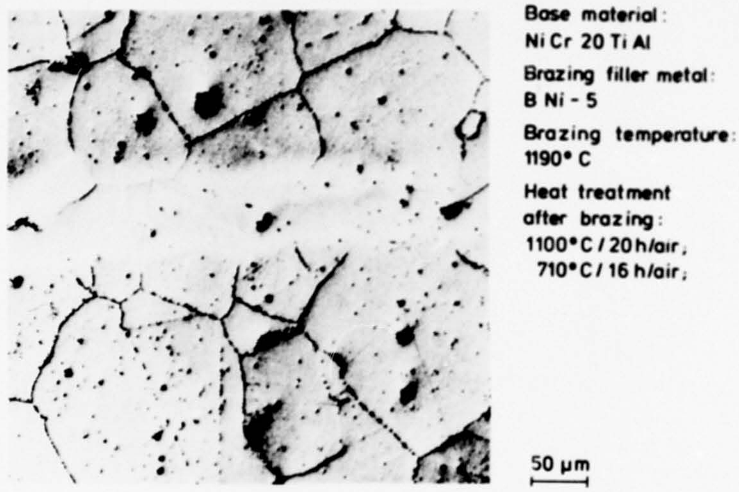


Fig. 2 NiCr20TiAl/BNi-5 brazed joint, heat treatment after brazing: 1100 °C/20h/air; 710 °C/16h/air

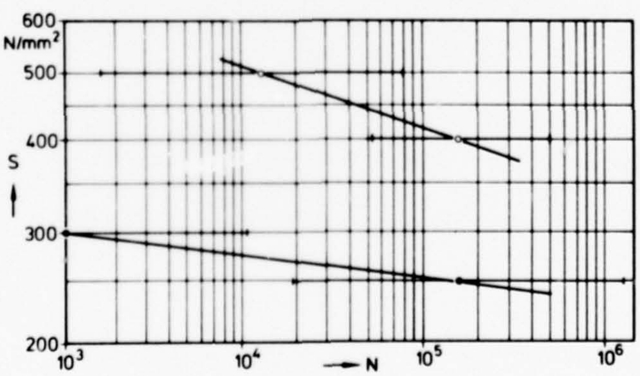


Fig. 3 Fatigue behaviour of NiCr20TiAl/BNi-5 brazed joints

Base material:	NiCr20TiAl	Stress ratio: R=0,1
Brazing filler metal:	BNi-5	Heat treatment after brazing:
Vacuum:	10^{-5} Torr	o 1100 °C/2oh/air
Brazing temperature:	1190 °C	710 °C/16h/air
Specimen shape:	A = ø 9 mm	o 710 °C/16h/air
	ground	Test temperature: 20 °C

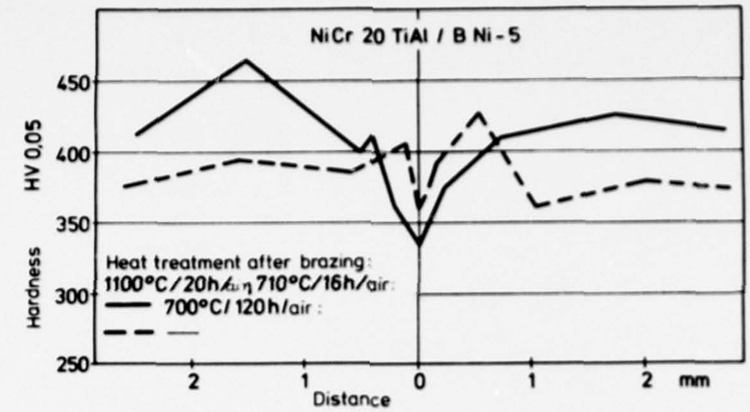


Fig. 4 Hardness of the brazed joint after a heat treatment

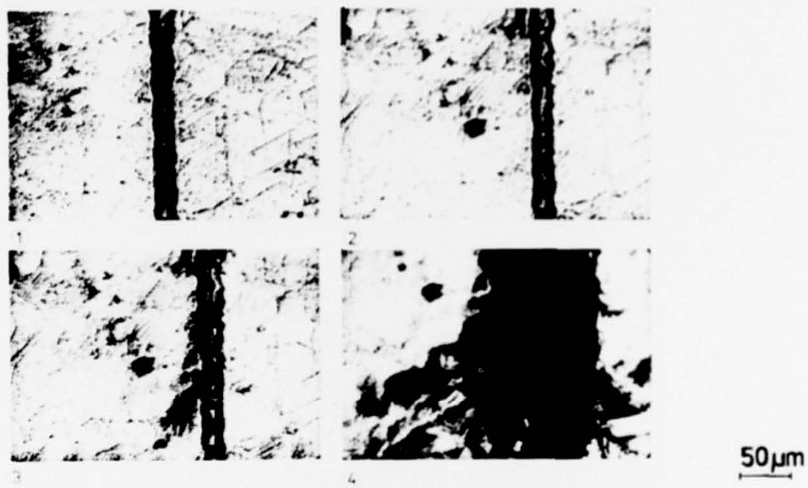


Fig. 5 Plastic deformation of NiCr20TiAl/BAu-4 under static loading and 400 °C test-temperature

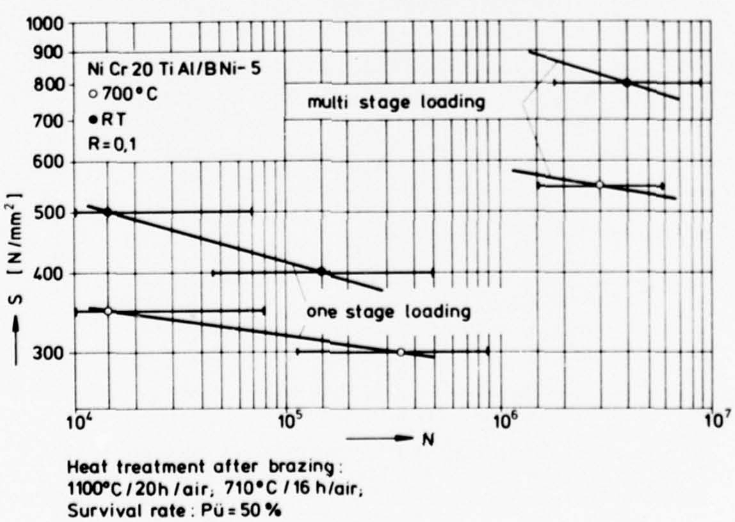


Fig. 6 Fatigue behaviour of NiCr20TiAl/BNi-5 brazed joints

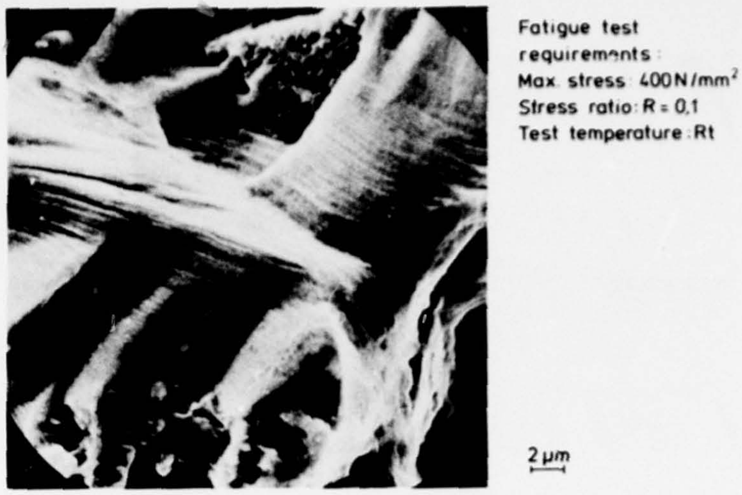


Fig. 7 Electron micrograph of striations on fatigue-loaded NiCr20TiAl/BNi-5 brazed joint

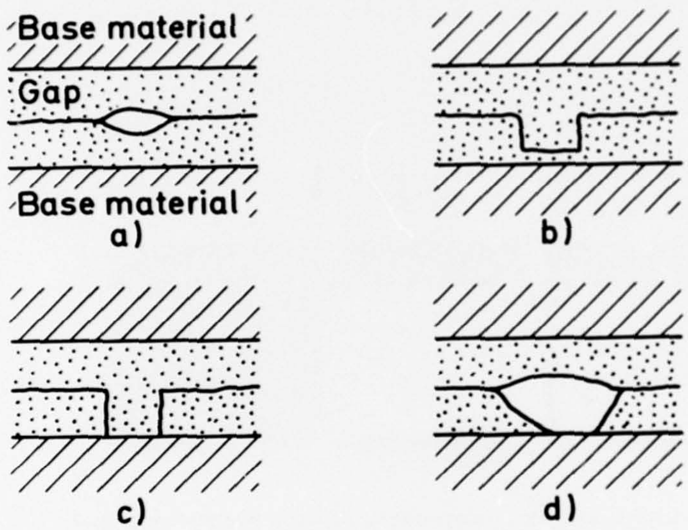


Fig. 8 Schematic representation of faults in brazed joints

Fig. 9 Fractured surface with a blow-hole (300 : 1)

Fig. 10 Riveted window section of a failed Comet aircraft

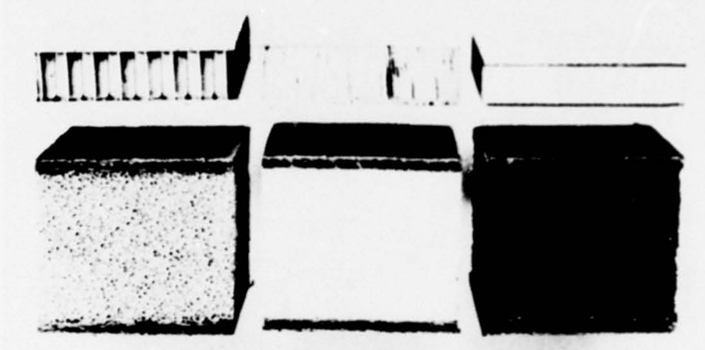


Fig. 11 Light-weight constructions with honeycombs and polymer foams

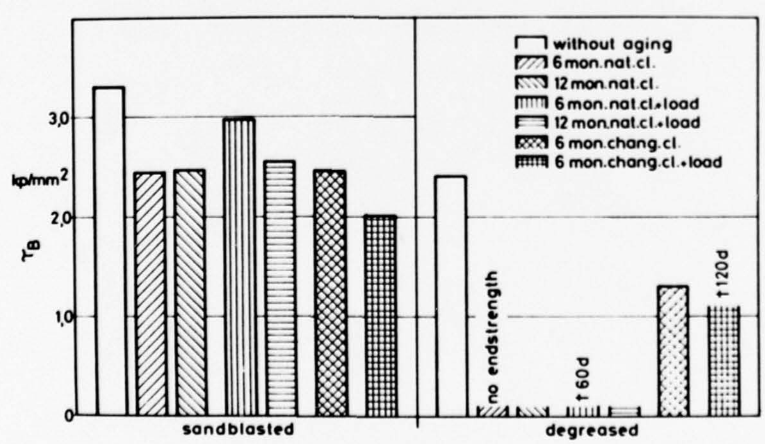


Fig. 12 Residual strength of steel bonds after different aging processes. Adhesive: modified epoxy-resin

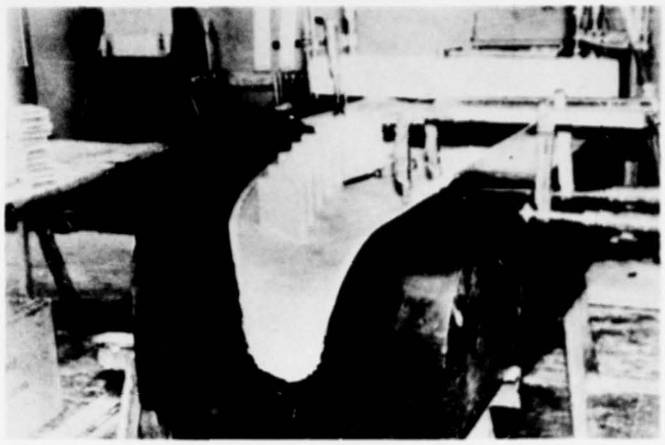


Fig. 13 Interior of an aeroplane glass-reinforced unsaturated polyester. Adhesive: modified epoxy resin

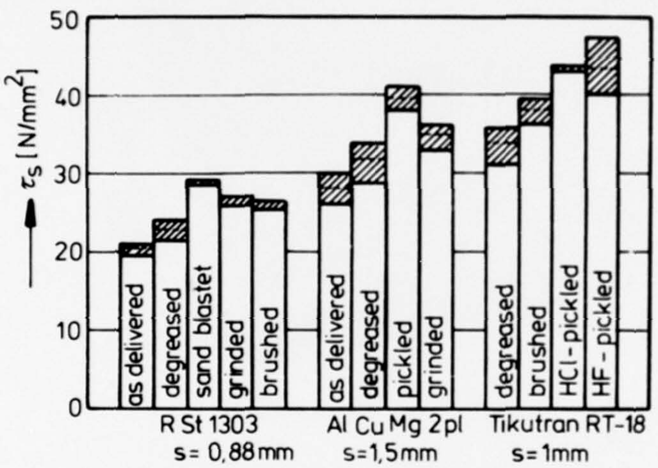


Fig. 14 Shear strength of metal bonds with different surface preparation

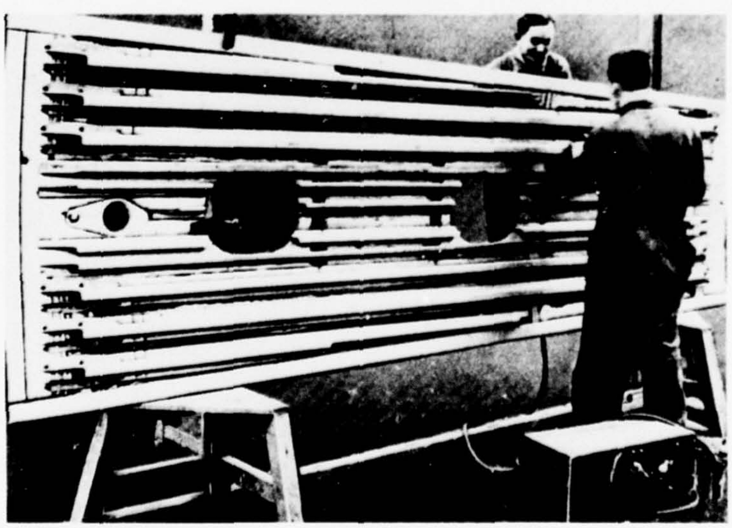


Fig. 15 Adhesive bonded stiffening sections in an airfoil

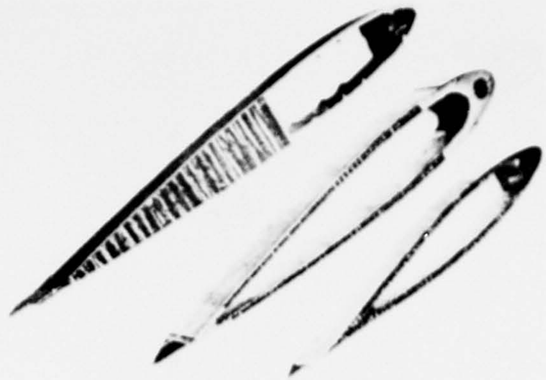


Fig. 16 Rotor blades as bonded honeycomb structures

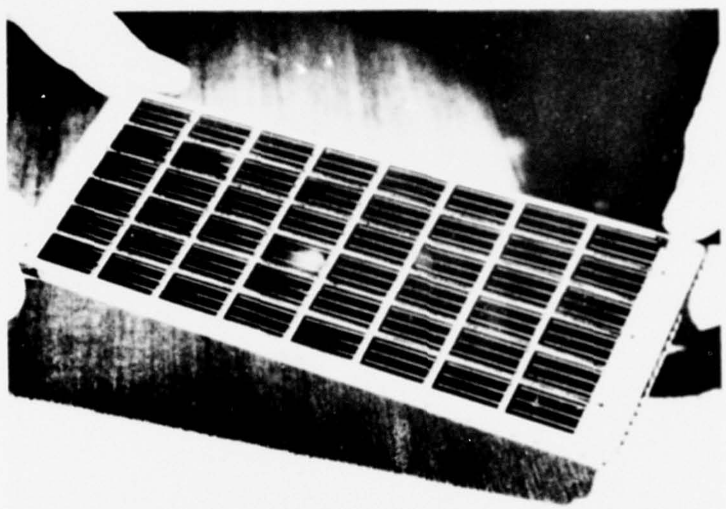


Fig. 17 Solar cell of the Ariel III Satellite on a honeycomb plate

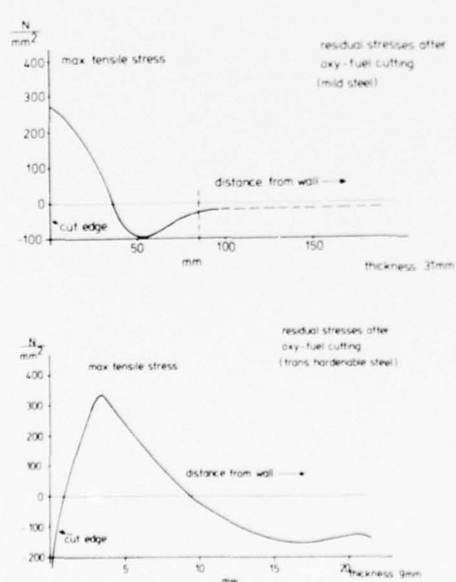


Fig. 18 Residual stresses of flame cutted samples as a function of cutting depth

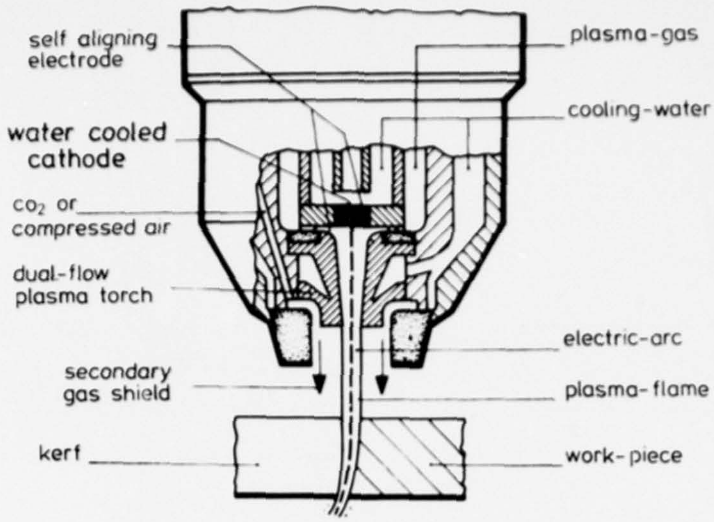


Fig. 19 Schematical drawing of a dual-flow plasma-torch

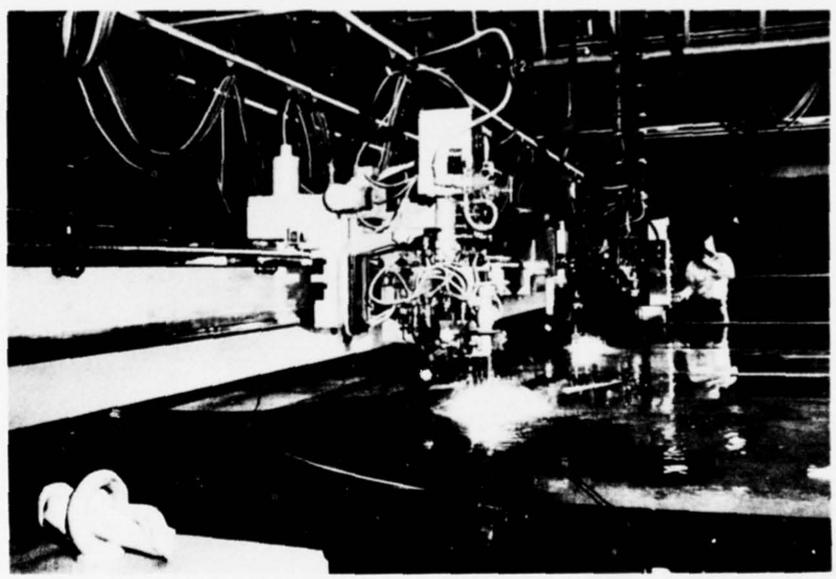


Fig. 20 Cutting procedure under water

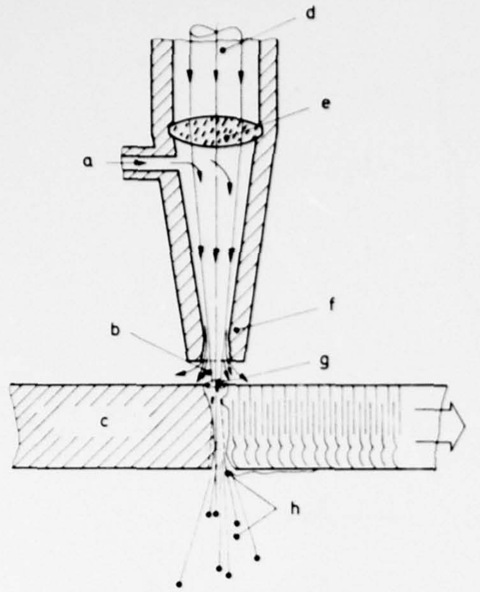


Fig. 21 Non-oxidizing cutting
a) inert gas
b) gas leakage
c) workpiece
d) laser beam
e) focusing optics
f) cutting nozzle
g) focus spot
h) fused metal

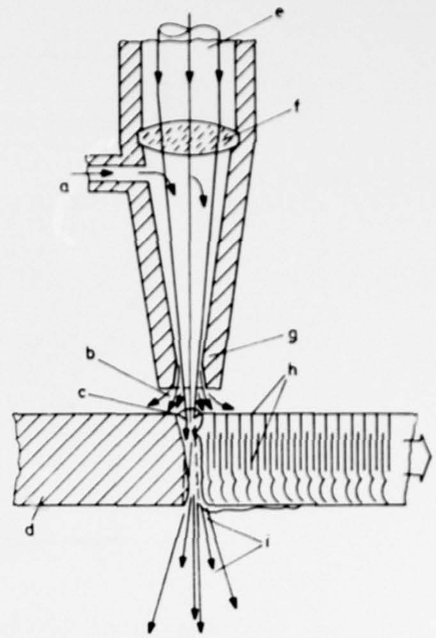


Fig. 22 Oxy-fuel-cutting with laser
a) oxygen
b) gas leakage
c) focus spot
d) workpiece
e) laser beam
f) focusing optics
g) cutting nozzle
h) surface
i) removed oxid

		Fields of Application				
		Abradable Gas Path Seals	Hard Counter Coatings	Wear Resistant Coatings	Thermal Insolation	Maintenance Spraying
Thermal Spraying Methods	Plasma Spraying	+	++	++	++	++
	Flame Spraying (Wire)	O	O	O	O	+
	Flame Spraying (Powder)	++	+	O	+	+
	Detonation Gun Process	O	O	++	++	+

O No Application
++ Main Application
\+ Application Possible

Fig. 23 Application of the thermal spraying processes in the aircraft-engine fabrication / 25 /

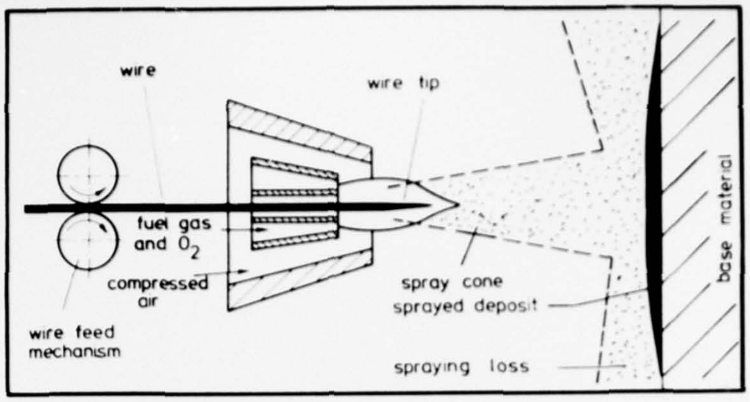


Fig. 24 Principle of the flame-spraying process

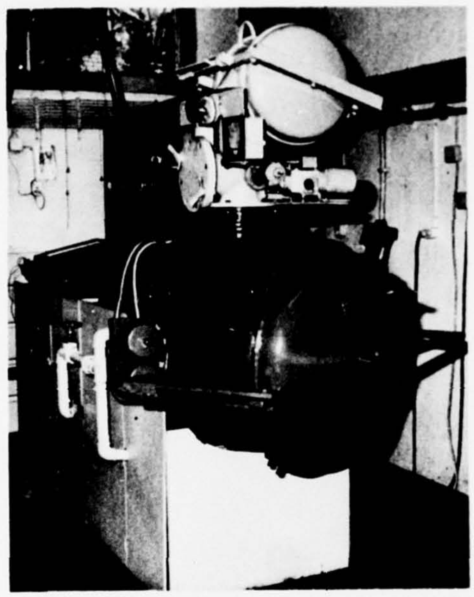


Fig. 25 Inert gas chamber

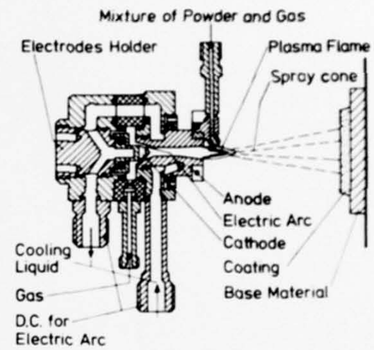


Fig. 27 Principle of the plasma spraying process

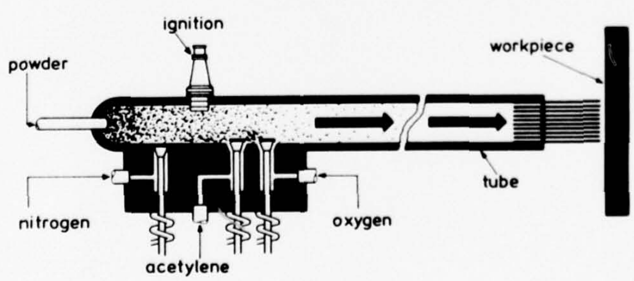


Fig. 26 Principle of the detonation-gun process

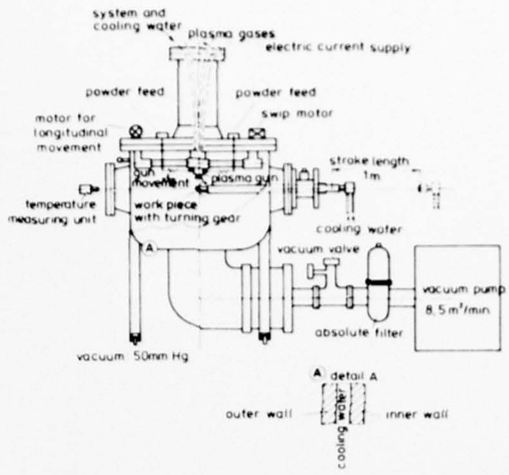
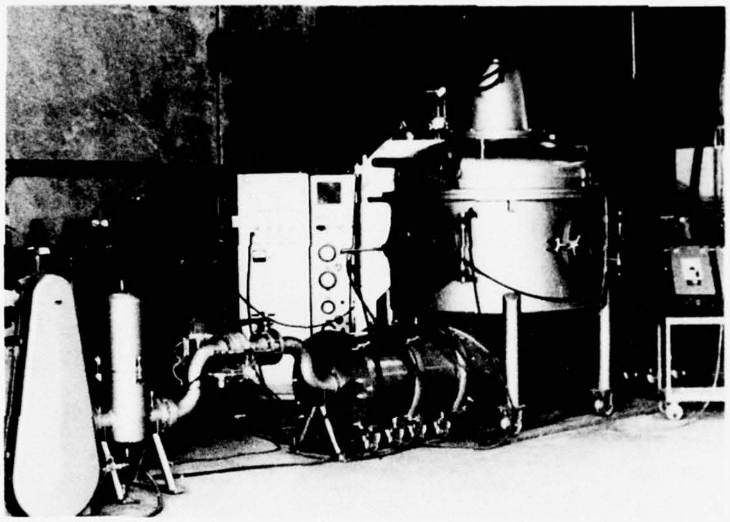


Fig. 28 Equipment for the high-energy plasma coating process

a) Schematical drawing / 21 /



b) Equipment (Foto electro-plasma)

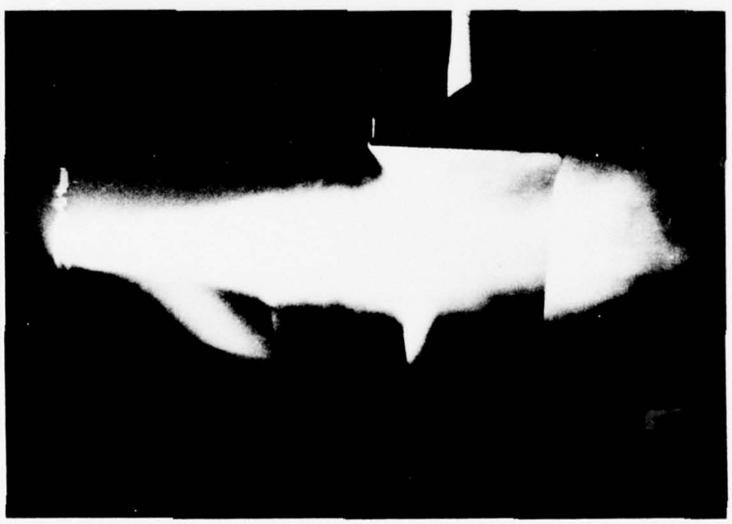


Fig. 29 Plasma stream with the superimposed transferred arc (Foto electro-plasma)

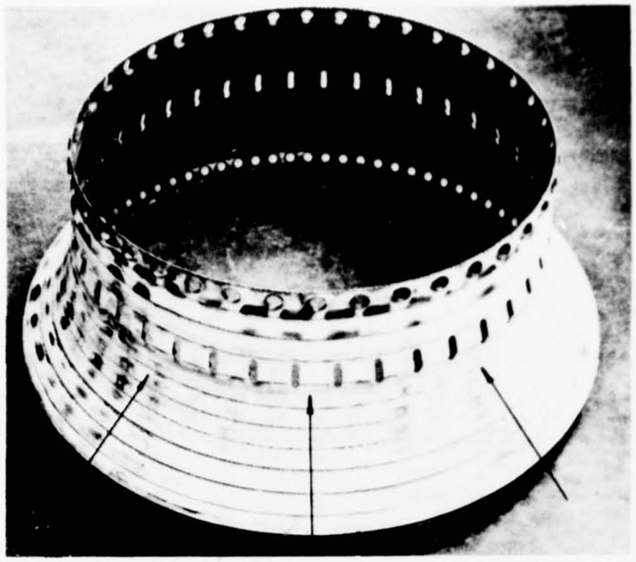


Fig. 30 Inner combustion chamber (Hastelloy X) / 22 /

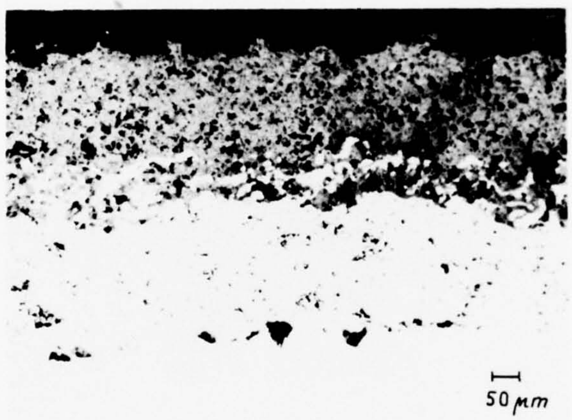


Fig. 31 Microstructure of a magnesium-zirconate coating with a bond coat of Ni-Al / 22 /

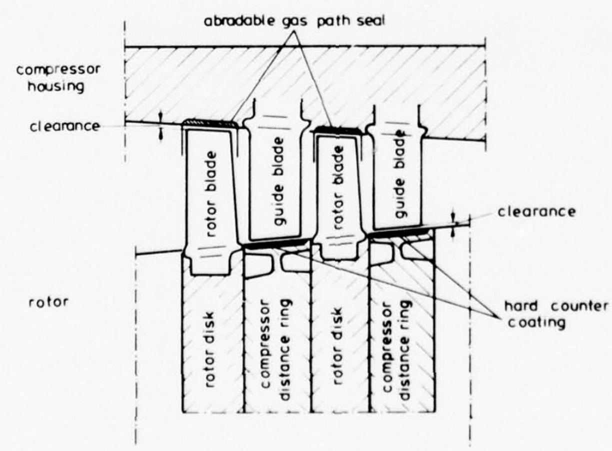


Fig. 32 Abradable gas path seals / 25 /

Types of Materials Used	Operating Temperature (°C)	Hot Spraying Process
Aluminium-Silicon Alloy with Polyester	350	Flame Spraying
Aluminium	400	Plasma Spraying
Nickel 75 - Graphite 25	540	
Nickel 85 - Graphite 15	640	Flame Spraying
Nickel - Chromium - Boron Nitride	700	
Copper - Zinc - Silver	350	
Nickel - Aluminium	920	Flame Spraying
Nickel - Chromium - Aluminium	950	

Fig. 33 Material for abradable seals / 25 /

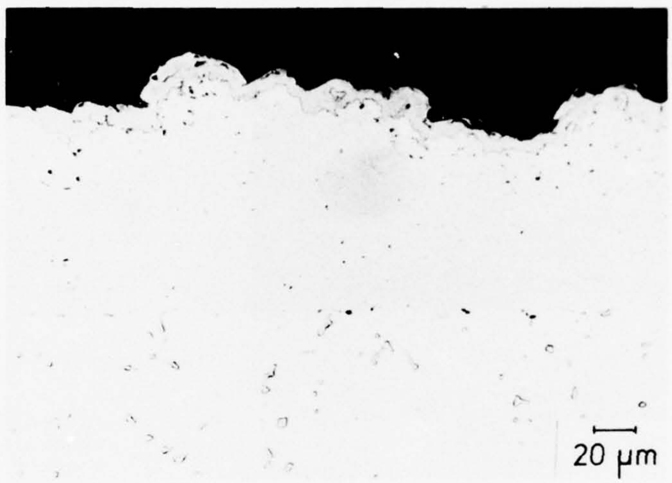


Fig. 34 Microstructure of a CoCrAlY-coating without heat treatment / 26 /

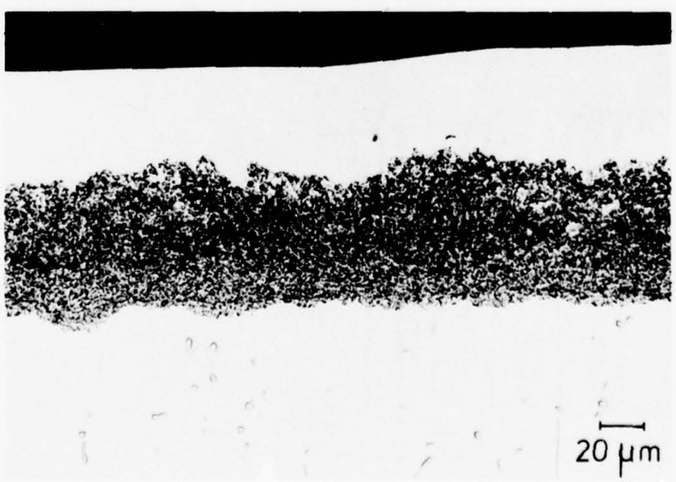


Fig. 35 Microstructure of a CoCrAlY-coating after diffusion treatment / 26 /

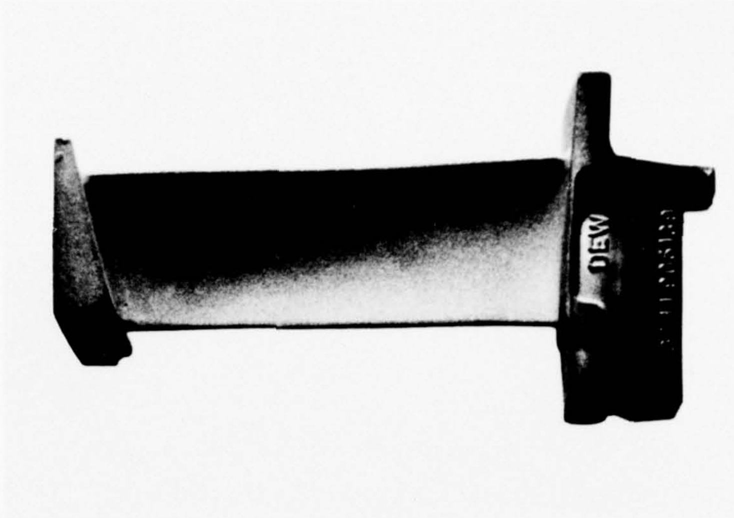


Fig. 36 Turbine blade coated with CoCrAlY / 26 /

Fig. 37 Turbine housing of a rocket engine / 26 /

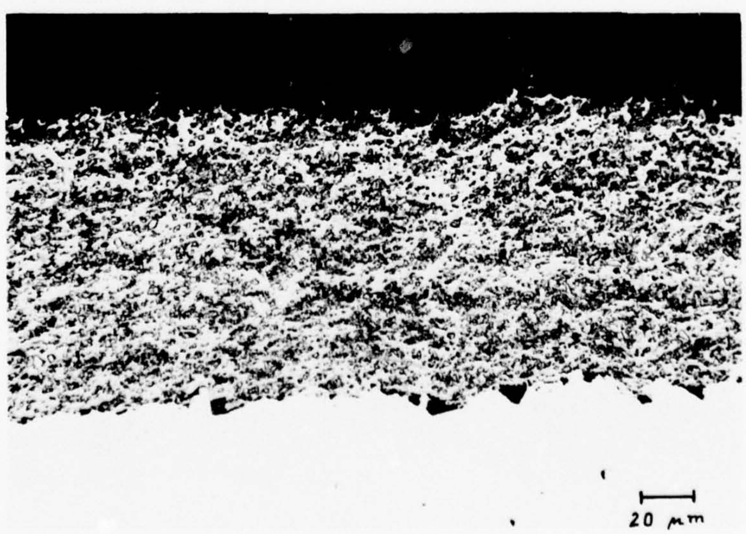


Fig. 38 Microstructure of a wear resistant WC-Co-coating sprayed in the vacuum by transferred arc / 26 /

ASPECTS OF THE MECHANICAL AND ENVIRONMENTAL BEHAVIOUR OF JOINTS

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1. SUMMARY

The strength of structural components is often limited by the mechanical and environmental behaviour of joints, like weldments, brazements and adhesive bondings. The properties of this inhomogeneous parts are different from the behaviour of the base materials. Inside the seam they depend on the heat treatment and residual stresses. So many tests are developed to examine the behaviour of joints. The basic principles of these methods like fracture mechanics, fatigue tests and tests under environmental conditions are discussed. Applications are presented in some examples of TIG, EB and resistance weldments, high temperature brazements and bonded structures. Also the detection of defects in joints in a nondestructiv manner like the application of holography and acoustic emission is discussed in some new developments and compared with the conventional methods like ultrasonic or X-Ray testing.

2. INTRODUCTION

Applications for high-strength materials having good specific strength depend greatly on the strength and stability of the joints in a jointed part. Frequently the welding zones form critical regions which may be decisive for the safety of entire components. Thermic jointing will cause structural changes in the materials which result in modified mechanical and technological properties as compared to the non-affected base material. In addition there may be defects in the welds forming geometrical notches in the form of pores, cavities, cracks as well as discontinuities at the surface and lack of fusion which, in conjunction with local stress concentrations due to unfavourable weld configurations, result in unfavourable loading conditions of the structures in question. Multi-dimensional stress states which can occur even without external loading, exclusively due to residual stresses of the first, second and third kind, may locally exceed the rupture strength of the material and, depending on temperature, cause additional defects in the form of hot or cold cracks with extremely small notch radius. Depending on their orientation with respect to the loading direction and to the weld they can become starting points for cracks subject to steady-state propagation or, in the extreme case, instable propagation.

Recognising the potential hazard of these defects, considerable efforts have been undertaken for a long time to detect and/or estimate as part of quality control inspections the effects of these defects, especially in welding seams. In order to be able to assess their hazard the defects must be known, for one, on the basis of their relevant charac-

teristics such as size, their orientation with respect to the load application, and their configuration. For another, the mechanical and technological characteristics of the material in the vicinity of the defect must be determined, especially its toughness which provides information on the hazards of crack propagation.

It is only recently that it has become possible to determine feasible toughness data on the basis of fracture mechanics. This approach provides the additional capability of estimating reliable defect magnitudes in real structural components.

However, difficulties arise in the complex bond in the welding zone itself. Since it is often the case that neither the defect characteristics named above nor the materials characteristics and stress states at the defect location can be determined precisely, a fracture mechanics study cannot be accomplished without significant simplifications.

Yet it is impossible to forgo such a determination because it is frequently the only means of acquiring results on the strength characteristics of the jointed parts which are subject to numerical evaluation.

Therefore, the following are prerequisites for such a safety analysis:

1. information on the existing loading state such as external cyclic, dynamic or static types of loads, and residual stresses which may achieve very high values on the surface of welds in the vicinity of discontinuities at the surface;

2. information on the mechanical and technological characteristics of the hazard-exposed structural zone under the prevailing environmental conditions;

   and

3. the non-destructive testing for existing defects.

3. MECHANICAL BEHAVIOUR

3.1 MECHANICAL STRENGTH PROPERTIES

Crack propagation is significantly determined by the mechanical characteristics and geometrical orientation of the individual structural zones of a weld. In tensile testing according to DIN 50 120 the strength properties can be determined only to an incomplete integral value which covers all the weld areas. Differentiating precision strain gauge measurements using strain gauges of 0.6 mm grid length, on the other hand, will yield information on the stress-elongation behaviour of the base material, the heat-affected zone and the weld metal in the technically interesting area of elastic-plastic transition. Measurements performed on high-strength, maraging steel types welded by different welding processes showed considerable differences in the o.2-boundaries of the weld metal and in the HAZ compared to the base material, refer to Fig. 1 / 1 /.

Similar differences are found in the deformation characteristics of the individual areas of high-temperature brazed joints / 2 /.

In adhesive-bonded metals these differences are even more pronounced and, moreover, are further aggravated by time-dependent creep processes in the adhesive / 3 /.

Information on the deformation behaviour will yield initial information on the loading of the individual partial areas of the weld. Moreover, it forms one of the significant prerequisites for fracture mechanics computations, especially with respect to COD and dynamic fracture toughness values. In particular, the change of the yield point at higher loading rates must be taken into consideration / 4 /. Fig. 2 shows the reduction of this value for a steel material and its electron beam fusion weld. In addition, this Fig. shows that the weld includes the areas subject to greater brittleness. However, since the safety of a structural component depends on these zones the consideration of fracture mechanics should preferably be centred on the weld so that for the high-strength materials frequently used in aircraft construction the principles of linear-elastic fracture mechanics are preferred among the testing procedures described below, rather than the techniques of general yielding fracture mechanics.

3.2 CRACK INITIATION AND ARREST

The crack initiation behaviour of welds has been repeatedly studied on large specimens in critical weld areas / 5 /. Corresponding to the practically occurring cases of cracks oriented vertical and parallel to the weld, the specimens have both weld orientations so that both, constant stress and constant elongation are present.

Difficulties arise especially with respect to optimum positioning of the notches, for instance in certain regions of the HAZ. Apart from their limited width their profile through the plate thickness is usually irregular so that necessarily several zones are affected. Consequently, studies of small specimens are required for this purpose. The concepts used

for the calculation of crack initiation are crack toughness measuring procedures to determine the stress intensity factor K_{Ic} and to measure the COD. Test procedures include notched bar tensile tests as well as static and dynamic notched bar bending tests.

The aspect that existing defects become instable and start to propagate is of great interest from the point of determining the hazard of defects but is secondary to the crack arresting concept in several respects / 6, 7 /.

This concept presupposes that a crack propagates and determines the capabilities of the material to reduce the crack propagation rate and to arrest the crack. Since the toughness of the material is usually lesser with respect to propagating cracks that for static cracks, values developed under this concept will provide greater safety against failure of the materials. In particular, this concept is of interest for welds involving tough portions of the base material and the highly different structures in the weld. However, its application and the interpretation of the results are still faced with difficulties since not all the dynamic effects such as shock wave propagation and the like are completely clarified.

Initial information on the crack arresting capability of a material can be obtained through the Robertson / 8 / and Pellini / 9 / tests. Pellini prepared a diagram (FAD - Fracture Analysis Diagram) on the basis of such tests which, for the first time, established a relationship between nominal stress, crack length and temperature / 10 /. However, the FAD is still too crude a technique for testing welds.

3.3 STATIC FRACTURE TOUGHNESS

Linear-elastic fracture mechanics describe the stress state ahead of the tip of an incipient crack without plastic deformation of the material. Above a certain critical stress intensity, K_c, the crack is subject to instable propagation. Crack propagation vertically to the loading direction (K_{Ic}) is considered the hazardous application case.

This value is determined on the basis of force vs. crack opening diagrams of notched specimens (P-COD) whose profile is evaluated by means of various procedures (pop-in, secant method, maximum force / 11-13 /.

Linear-elastic fracture mechanics will fail in the case of materials having greater toughness and greater plastic components ahead of the crack, unless the required twodimensional plane strain state is maintained as a result of very large test specimens or low temperatures. At this point the procedures of general yielding fracture mechanics are substituted.

While for the brittle materials a critical stress determines crack propagation, in this case the critical strain affects the fracture. This critical crack opening displacement is referred to as the COD or COS (Crack Opening Stretch) value.

This description of plastic deformation is based on the model proposed by Dugdale / 14 / which is based on the following considerations:

1. On the basis of elastic-plastic behaviour a hypothetical crack is considered whose length is composed of the true crack length and a plastic deformation zone whose length is d.

2. Beyond this hypothetical crack length a the material shows purely elastic behaviour.

3. A constant yield stress prevails in the plastic deformation zone of length d.

The COS value can be determined by means of different procedures. Thus, for instance, the COD is determined by means of the clip gauges conventionally used in linear-elastic fracture mechanics, and converted to the COS value. The conversion ratio is based on the concept that the crack sides pivot about a point ahead of the crack tip. In addition, direct COS measurements can be accomplished by means of optical surface measurements by the removal or replica method / 15 /.

Difficulties still exist in demonstrating a relationship between the measured COS value, the stressing of the component and the crack length in components subject to plastic dedeformation. One approach in this direction has been shown by Burdekin et al / 16, 17 /, who determined a "design curve" representing non-dimensional "crack opening" as a function of strain in the crack zone, refer to Fig. 3.

Strain in the crack zone is expressed by a multiple of the elastic strain of the material at the yield point. This "design curve" can be used to estimate the critical defect magnitudes for given strain in the defect zone. However, these relationships, too, apply only to limited plastic deformation ahead of a crack tip.

However, the so-called J-integral introduced into fracture mechanics by Rice / 18 / can be used to predict the crack propagation behaviour even in the presence of great plastic deformation at the crack tip. Various methods for the experimental determination of J upon incipient crack propagation are being tested at the present time / 19-21 /. However, some time will pass before standardised procedures have been developed.

Rice initially defined the J-integral for two-dimensional, non-linear elastic problems. This is a closed line integral along a path enclosing the crack tip. The integral is independent of the integration path and, therefore, represents a measure for the stress singularity at the crack tip.

The following points are important for the practical applicability of this integral / 15 /:

a) J can be determined from the change of the energy required for deformation with changing crack length.

b) In the case of linear-elastic behaviour, J is equal to the energy release rate, G.

c) The form initially valid for non-linear elastic deformation can also be used for elastic-plastic deformation if the loading is monotonous at every point of the specimen, i. e. if there is no local load relief. The J-integral procedure cannot be used without modification for the description of steady-state crack propagation. However, it is suitable for describing incipient steady-state crack propagation.

Since the J-integral has hardly any significance for the determination of the strength behaviour of welds in high-strength materials, this subject shall not be discussed in detail here.

If fracture mechanics are applied to welds the prerequisites of linear-elastic behaviour to fracture (predominantly plane strain state) will predominate for all zones of a weld.

In this case the determination of the individual structures as a function of the welding process used is faced by significant problems as a result of the usually irregular weld configurations. For conventional welding processes, carefully prepared specimens with K-welds can be used where the HAZ is oriented approximately vertically to the surface of the plate, refer to Fig. 4, / 22 /. Incidentally, additional lateral notches can be machined into the zones of such a K-weld which, on the one hand, guide the propagation direction of an incipient fatigue crack and can prevent its deflection into adjacent areas, and, for another, this technique can be used to check whether the K_{Ic}-values determined are still valid when the specimen thickness is near the limit of the minimum plate thickness required by ASTM. Under load exposure the notches will produce immediately under the specimen surface a multi-axis stress state which especially reduces the plastic regions developing along the plate surfaces so that a state of predominantly plane strain is achieved even of specimens having a lesser plate thickness. Where this state already exists, the same fracture toughness values will be measured on non-notched and laterally-notched specimens.

If this technique is used to test TIG and EB welds on high-strength, maraging steel, marked differences in the fracture toughness values will be found for the individual structures in the weld, refer to Fig. 5.

In the case of both welding processes the fracture toughness in the weld metal is reduced to approximately 60 % of the values applicable to the base material. This is due to microsegreation producing austenitic components at the dendritic boundaries in the weld metal. When exposed to load these components will fail, thus promoting crack propagation. Considerable improvement of toughness can be achieved by reducing this segregation through solution heat treatment / 23 /.

The different behaviour of the fracture toughness of these welds as a function of test temperature and loading rate is represented in Fig. 6.

While the base metal reacts with sensitivity to the temperature decrease and increased loading rate, the weld metal does not have this dependence. This is indicative for the great contribution to crack propagation of the austenitic components which is even insensitive to loading rate and temperature effects / 23 /.

In Fig. 7 the fracture toughness values of the welds achieved on this steel grade by means of different welding processes are compared. In addition, the values for a high-strength, quenched and tempered steel grade (X38CrMoV51) have been plotted for comparison. It is clearly seen that the values for the weld metal are variable with the welding process used and that different processes are optimum for different materials. In every case, however, those welding processes yield the best results which guarantee maximum purity during the welding process.

steel grade	investigated area	K_{Ic} $[N/mm^{3/2}]$	maximum of allowed failure dimension under $\sigma=1200[N/mm^2]$ in mm
X 2 NiCoMo	base metal	3200	7 x 11
18 8 5	TIG weld	2090	3 x 4,5
	EB weld	1890	2,5 x 4
X 38 CrMoV	base metal	1180	0,9 x 1,4
5 1	TIG weld	870	0,5 x 0,8
	EB weld	1290	1,2 x 1,8

If it is intended to manufacture components from these steel grades the question arises as to the type of defect which must be detected via non-destructive testing in order to sustain a maximum load of 120 kp/mm^2 without hazard - not including the effects of residual stresses. Stipulating an elliptical configuration for internal defects whose width and length shall have a ratio of 1 : 3, the dimensions communicated in the above compilation will be obtained. It is likely that critical defects in the base metal, a maraging steel, can still be detected. However, weld testing on components made of this steel grade already requires extreme care since defects having the dimensions of 2.5 x 4 mm^2 must not be overlooked.

Still greater requirements must be imposed on the defect detection level by non-destructive testing when the hot-working steel grade X38CrMoV51 is used. And the problem becomes almost insoluble where this steel grade is TIG-weled: defects having dimensions of o.5 x o.8 mm^2 must be detected.

This example also explains the problems encountered in earlier years on the Polaris missiles. The first of these missiles were made of TIG-welded H 11 steel which is highly similar to the X38CrMoV51 material. Subsequently a maraging steel was used which had greater fracture toughness and, therefore, was less susceptible to defects / 22 /.

Studies performed on diffusion-brazed Ti-Al6-V4 / 24 / yield a similar deviating behaviour between brazed joint and base metal. While all other strength data almost agree, the fracture toughness of the joint is markedly lower. This reduction is due to the residual copper content in the joint, refer to Fig. 8. In this case the diffusion can be controlled by varying the brazing parameters, resulting in optimization of the toughness properties of the joint.

While the stress relationships and the applicable laws are relatively easy to analyse in these types of joints, the conditions for adhesive bonds are more difficult to grasp. Therefore, only empirical studies exist to this date. Among these so-called "Aufklapp"-test / 3 / has proved to provide the greatest amount of information.

The adhesive layer is placed between two base material specimens, and the crack initiated. The force is measured as a function of opening the adhesive joint which is equated to crack opening, refer to Fig. 9. These test results are highly dependent on the geometry of the jointed parts, and the stress state will be subject to continuous change throughout the test as a result of creep phenomena.

Under this type of load the crack will propagate similar to crack propagation in the boundary layer or in a zone near the boundary layer in a peeling test since these are usually the most crack-susceptible zones in adhesive metal bonds. This will predominantly determine changes in the boundary layer as a result of varying surface treatment or due to aging effects.

3.4 DYNAMIC FRACTURE TOUGHNESS

The dynamic fracture toughness of many materials differs from the fracture toughness determined in static tests because many input magnitudes such as the yield point are subject to change. The dynamic toughness properties of joints can be determined by means of notched bar impact tests on bending specimens using an adequately sharp notch in accordance with the method communicated by Cabelka / 25 /. This technique will produce high strain rates in the micro range which, depending on the loading rate (approximately 0.5 - 5 m/s), can range between 10^4 and 10^6 %/s / 26 /. Subsequently the brittle fracture zone can be separated from the ductile fracture zone by means of the impact energy vs. temperature plot applicable to different impact rates. The energy required to deform and destroy this specimen represents an integral quantity which states the impact energy under notch effect and increased loading rate as a function of temperature. This plot will yield neither the components of elastic and/or plastic deformation energy, nor the energy components required for the partial processes of crack initiation and crack propagation / 27 /.

Therefore, the test was "instrumented", i. e. the force and the deflection of the specimen are measured by means of electronic pick-ups. In principle, this will make it possible to associate the partial processes of the fracture with the plotted curve. Thus, similar to the P-COD-curves, three regions are obtained which are associated with purely elastic force increase, plastic deformation and crack propagation. The maximum force is stated as the initiation of crack propagation. From this plot the dynamic stress intensity factor K_{Id} can be determined which has greater significance for testing joints than the K_{Ic} factor.

This also applies to macroscopically slow loading rates in those cases where an already propagating crack causes high strain rates in the microscopic region at the crack tip. For instance, where a crack subject to propagation is formed in a weld in the HAZ (static fracture toughness K_{Ic}), it will be stopped upon transition into the non-affected base metal or into the weld metal only if the dynamic fracture toughness values (K_{Id}) are adequately high in these areas. Consequently, the K_{Id} values are also the decisive criterion for stopping propagating cracks / 22 /. The additional velocity embrittlement will cause a reduction of fracture toughness whose minimum K_{Id} value is reached in the impact loading range of $\dot{K} \approx 10^7$ N mm$^{-3/2}$s^{-1} / 28 /.

Measurements of K_{Id} do not yet represent a tried and tested technique. While the high loading rates can be realised in notched bar impact testing machines or drop weight testing machines, considerable instrumentation problems arise. These start with the fact that the force is measured at the tup or in the vicinity of the supports so that it will not be representative for the loading at the crack. In addition, the significantly smaller mass of the specimen is accelerated upon impact of the tup and will deflect. This will result in an initial load increase and subsequent decrease, refer to Fig. 10, the so-called intertial peak. Moreover, as the result of impact excitation shock waves will propagate in the specimen which result in uncontrolled reflection and, hence, stress conditions at the crack tip. Finally, the conventional clip gauges have too much intertia to measure the crack opening rapidly. Last, not least, in many instances there is a lack of information on the existing yield points which, according to Fig. 11, is required in addition to the temperature dependence of K_{Ic} and σ_{ystat} in order to determine K_{Id} / 29 /.

The actual load at the crack is now subject to first feasibility studies using photoelastic materials an these have yielded results which deviate greatly from the previous stipulations / 3o /.

Moreover, this author's invenstigations have shown that the assumption of initial crack propagation at the load maximum is incorrect. In order to show this, the load vs. time profile at the hammer blade an the acoustic emission of the notched bar specimen have been plotted in Fig. 12 for two experiments. The sounds of the plastic deformation and the slap of the tup was eliminated in preliminary experiments by selecting suitable transducers and corresponding frequency-filtering. The sound pulses found in this sample made of C 6o are already equivalent to crack propagation, as confirmed by subsequent metallographic studies. In some cases propagation is initiated already at very low loads.It should be kept in mind that the specimens used for these experiments were cracked only partly, not all the way through, so that the loading required to calculate K_{Id} does not even occur. The load vs. time curve which slopes downward at a faster rate with greater and more numerous sound pulses (= greater incipient crack) correlates with this acoustic emissions.

As a result of these very recent studies we shall not present any results obtained to date from joints which are still based on earlier stipulations.

3.5 FATIGUE

Since aircraft components are predominantly exposed to cyclic loading, the developement an profile of defect characteristics under cyclic loading are of decisive importance for the service life of a component / 31 /. The fatigue process can be sub-divided into different levels, refer to Fig. 13, initial slip phenomena occur after only a few loading cycles which initiate the work hardening process in the crystallites. These work hardening processes are completed only when saturation of the plastic strain amplitude takes place. At the end of this process, sub-microscopic crack initiation occurs / 32 /. The crack initiation process is subject to two stages, refer to Fig. 14.

During the first stage the incipient cracks, most of which are smaller than the crystallite, start propagating along the slip planes and slip bands at a rate of a few Angstroms per load cycle. Often stage II sets in even when the first grain is left, where the crack propagates vertically to the applied stress an corresponds to technical-scale crack propagation. Depending on the type of material an loading this directional change will take place sooner or later.

Unlike brittle fracture, plastic deformation is an important parameter in fatigue cracking. In many instances the application of linear-elastic fracture mechanics appears more justified for crack propagation under cyclic loading than for brittle fracture problems since the stress level at which a crack will propagate is relatively low. Therefore, theoretically speaking, the plastic zone at the crack tip is small, which makes analytical treatment difficult.

The first consideration to determine the numerical crack propagation rate will lead to the point where the measured crack length of a specimen obtained from a corresponding test is plotted as a function of the number of cycles, thus obtaining the slope of a curve which represents a measure of the crack propagation rate. For this purpose Paris developed the crack propagation relationship under cyclic loading with the aid of fracture mechanics. However, this relation has various weak points and was therefore supplemented by Forman / 33 /.

$$\frac{da}{dN} = \frac{c \cdot \Delta K^m}{(1-R)\ K_c - \Delta K}$$

Unlike the formula by Paris this relation includes the mean stress effect and the upper boundary of crack length. But even Forman failed to take into consideration for his formula that even components having incipient cracks have fatigue strength.

The constants were determined with the aid of some crack propagation tests, and from these the crack propagation was precisely calculated for specimens of the same

charge / 34 /, but at different stress amplitudes an mean stresses, refer to Fig. 15.

Another effective magnitude for the crack behaviour of materials subject to cyclic loading is the problem of damage accumulation, i.e. the determination of crack propagation under irregular cyclic loading / 35 / .

The damage accumulation problem, too, can be treated on the basis of the Forman relation. This is based on the root mean square value (rms value) derived from a random process or from a load collective. The significance of the rms value as a characteristic damage parameter under cyclic loading is subject to dispute. One advantage of its application is that it is not necessary to know the pricise loading profile. On the other hand, sequential effects may be disregarded. But it may be precisely these sequential effects which have decisive significance for the life of a component / 36 /, especially in the event of high peak loads occurring individually or sequentially.

Recently these investigations are supplemented to experiments of Ziebart and Heckel / 37 /. They stipulate that the fatigue behaviour of a component is dependent on its shape an size. In order to describe this effect the fatigue process in the area of fatigue strength for finite life is explained as follows: A component includes defects of certain size in statistical distribution. The largest of these defects will propagate as a result of cyclic loading, resulting in permanent fracture.

The mathematical formulae for these two stipulations will yield a calculation procedure which allows a prediction of the fatigue life of a component as a function of shape and size.

A comparison of the fatigue life so calculated for three different specimen shapes to the values determined in actual single-stage tests has been plotted in Fig. 16. The testing of joints with their numerous and various structures is more difficult than this simplifying representation.

Fig. 17 shows the fatigue curves of the material X2NiCoMo 1885 and its TIG-welds after cyclic loading in a single-stage test. The achieved fatigue strength of σ_D = 500 N/mm^2 is relatively low so that the well-known, good strength characteristics are not achieved under cyclic loading / 38 /.

This ultra-high-strength steel will yield good data only in the fatigue strength range of $N < 5 \cdot 10^4$ cycles. These results, relatively low fatigue strength under high numbers of cycles to fracture, can be explained only by different damage mechanisms. Thus, the first microscopically visible cracks having a length of approximately 10 µm are formed in the capping passes an cover passes of the weld, where a pronounced dendritic structure is predominant. It is found that the origin of these cracks is at the dendritic boundary and that subsequently the cracks may branch out and change direction. This will result in retardation of crack propagation.

Sub-microscopic segregation can be identified after only 20,000 loading cycles. The effect of the structure, refer to Fig. 18, is seen clearly. Moreover, deformation traces develop at the embedded secondary phases which cause material separation in the boundary surface between inclusion and matrix, thus shaping the subsequent crack.

Another example for the highly differentiated damage profile is the behaviour of high-temperature brazing joints of super-alloys on the Ni base, refer to Fig. 19.

Thus, the formation of slip markings and the occurrence of fatigue crack structure on the entire fracture surface of a joint brazed with Ni-base filler metal is indicative for damage occurring prior to fracture / 39 /. Individual crystallites must be considered the nuclei of crack formation, changing their microstructure under cyclic loading and causing sub-microscopic cracks. These micro-cracks extending over the entire joint area unite into a major crack which, after additional loading, results in fracture.

Fig. 20 shows the fatigue crack of an individual crystallite on the fracture surface in the residual fracture region, where the crystallite is destroyed after forceful fracture.

4. ENVIRONMENTAL BEHAVIOUR

Environmental conditions have a capability, dependent of time, for greatly modifying the structure of a material and, hence, its failure resistance, and therefore have a significant effect on strength characteristics. Thus, almost all high-strength and high-temperature resistant metallic materials are subject to changes of their property over time which are further aggravated by the high stress gradients existing in joints.

This applies especially to joints of a non-metallic nature such as adhesive bonding, a technique used in aircraft construction for both, metals an plastics.

Since these adhesives are also plastics, even slightly increasing environmental temperatures can result in significant strength losses of the bonds, refer to Fig. 21.

Especially damaging is the effect of media on adhesive bonds since, especially in adhesive bonding of metals, some of the bonds are not water-resistant, or sub-surface corrosion takes place at the boundary surface.

The bonding strength is additionally weakened by mechanical stresses an allow. accelerated humidity diffusion, refer to Fig. 22.

The media effect requires special attention even in the case of welded or brazed joints because it es especially significant in fracture mechanics studies in the form of increased crack propagation. In addition to normal corrosion and the formation of local phenomena such as Evans elements, corrosion in crevices and the like, it is especially the selective corrosion types which must be expected in joints. Stress corrosion cracking in conjunction with the formation of local elements can result in a high prediction error for the life of components on the basis of fracture mechanics, due to the difference in the structures.

Surface protective measures such as coating and the like are quite able to prevent general corrosion; yet they may even become initiators of selective corrosion types due to changes in the coating.

4.1 STRESS CORROSION CRACKING

While under "normal conditions" as defined by linearelastic fracture mechanics there is no movement of the crack tip prior to instable crack propagation, subcritical, stable crack propagation can be caused due to cyclic loading or corrosion. The frequently measured endurance includes both, the incubation period and the time required to residual fracture. However, the incubation period might be a multiple of the time required for crack propagation / 40 /. Often, for instance, media flow during the measuring period will prevent the formation of sharp notches required for crack propagation. Therefore, Engell and Speidel / 41 /, recommend a separation of these two periods.

This crack propagation phase is sub-divided into stable crack propagation (delayed fracture) and instable crack propagation (forced fracture) above the K_{Ic} level, refer to Fig. 23. There is no crack propagation below a stress intensity of K_{Iscc}.

The ratio of K_{Iscc}/K_{Ic} is considered a measure for the stress corrosion cracking susceptibility. In the region of stable crack propagation (between K_{Iscc} and K_{Ic}) different functional relationships between stress intensity and crack propagation rate are found / 42, 43 /. Fig. 24 shows a schematic of these relationships. Endurance measurements under different initial intensities can be used to determine the boundary value K_{Iscc}.

The allowable size of a defect can then be determined by means of DCB specimens via the boundary value K_{Iscc}. Stress corrosion cracking is observed on several aircraft materials in different media. A review of these phenomena is provided in one of the early AGARD lecture series / 44 / . These have found the following significant effects:

The presence of Cl ions in Al alloys an austenitic steel grades results in the destruction of local covering layers. Electrolytes causing passivation represent the hazard for Mg alloys.

Special attention must be devoted to Ti alloys which in non-notched condition in aqueous solutions are entirely insensitive to stress corrosion cracking. It was only through some incidents of damage that attention was directed to the high sensitivity of notched specimens. Therefore, studies / 45 / have been conducted recently on the resistance of these materials whose results have been plotted in Figs. 26 and 27. In the NaCl solution the crack propagation rate is markedly higher than in air. Both critical values, refer to Fig. 27, K_{Iscc} and K_{Ith} (air) are lower than K_{Ic}, and the results are almost independent of the initial loading amplitude (K_{fmax}).

In the case of both of these alloys, however, stress corrosion cracking can be arrested. Therefore, a distinction must be made between the critical value where initial cracks start propagating and the value where the crack passes through the specimen without being arrested. Similar conditions apply to the TiAl6V4 alloy where, however, the values of K_{Ith} and K_{Iscc} achieve greater proximity.

In most materials subject to stress cracking it can be determined in general that susceptibility increases with increasing temperature and that the propagation rate depends on the stress intensity. Additionally, the effect of the loading rate is shown schematically in Fig. 25, / 46 /.

A striking feature is the reduced damage under greater loading rates. This effect is due to the different mechanisms of purely mechanical crack propagation and of the superimposed electrochemical loading. These mechanisms must be known precisely for any discussion of suitable corrective measures.

Two basically different concepts are involved in the discussion. Both are based on the stipulation that electrochemical phenomena promote mechanical crack propagation. The one concept is based on the assumption that the anodic part of the process contributes directly to crack propagation. In that case, reference is made to stress corrosion cracking (SCC). The other concept considers that the cathodic part of the corrosion process and, hence, the generation of hydrogen ions from the electrolyte, is the predominant cause. The ions are discharged at the metal surface and are either absorbed or adhere to the surface. The resulting hydrogen embrittlement results in a reduction of the critical K_{Iscc} value.

Several concepts have been developed to explain SCC, most of which can be classified into one of three groups. / 41, 47 /. The first group describes SCC as a selective electrochemical, anodic dissolution of the metal at the base of the crack while the second interprets the cause of SCC as being a reduction of the bonding force at the base of the crack resulting from the adsorption of specific ions. The last group explains stable crack propagation with the brittle fracture of thin surface layers.

Different model concepts have also been developed for hydrogen embrittlement (HE). The pressure hypothesis, / 48 /, interprets embrittlement as a result of high pressure causing the recombination of atomic hydrogen in cavities in the metal. Other concepts state that the cause is a reduction of lattice cohesion due to local hydrogen enrichment ahead of the crack tip caused by diffusion, / 49 /, or transport through moving dislocations, / 50 /.

The third theory, similar to SCC, is based on the adsorption of hydrogen and the resulting reduction of surface energy (adsorption embrittlement fracture hypothesis), / 48 /.

Which of these hypotheses applies in any concrete instance is often difficult to decide. As a result of the increasing availability of hydrogen there is danger of HE in acid-containing electrolytes, while SCC will occur with preference in alkaline electrolytes. Phelps, / 51 /, attempted a distinction between these two basic mechanisms by determining the endurance of specimens subject to different polarization. Fig. 28 shows the results obtained from measurements on different materials. He interpreted the endurance maxima determined by him as transitions from one mechanism to another. The reduced endurance due to anodic polarization was considered indicative for SCC while the reduction due to cathodic polarization was considered indicative for HE.

Since in cases a-c anodic polarization was required to achieve the endurance maximum, the cathodic part of the process was predominant in the currentless condition. In examples d to f this applies to the anodic part of the metal solution process while in cases g, h and i the reactions taking place in currentless condition cannot be identified. In cases c, f and i no fracture was identified at maximum endurance.

However, these results will not yield conclusive information on the dependence of crack propagation rate on the strong polarization generated since it is not clarified whether the polarization of the non-notched specimens used promotes the initial process or crack propagation.

A distinction between mechanisms by means of fracture surface studies is not feasible in the macroscopic range since the phenomena are highly similar. However, according to Nielsen, / 52 /, electron - microscopic replica fractography can be used to abtain certain information on the fracture mechanism.

In considering all of these investigations it must be kept in mind that they yield information only on crack propagation, not on crack initiation.

The mechanisms of the initial phase can have a variety of causes such as mechanical notching, damage to protective layers or other corrosion phenomena. However, these phenomena shall not be discussed in detail here.

4.2 FATIGUE CORROSION

Unlike stress corrosion cracking, fatigue corrosion cracking is usually a process predominantly determined by mechanical loading which is intensified by the electrochemical process. Thus, fatigue corrosion cracking can occur in any alloy and any pure metal in quite nonspecific electrolytes. In the case of fatigue corrosion crakking the cracks will develop only after the formation of corrosion fractures, some of which are quite large, and may become finer as they penetrate into the metal but remain very broad in all cases, as distinguished from the stress cracks. As a rule, fatigue corrosion cracking is trans-crystalline and is concentrated on a single crack.

The crack path is dependent on the size of the primary notch.

Crack propagation itself is affected by both, electrochemical and mechanical components. Thus, the factors reducing the repassivation current density have a favourable effect. The mechanical effect is clearly dependent on the frequency. Since the electrochemical process is time-dependent its effect fades with rising frequency, refer to Fig. 29.

The interaction of these components results in the failure of high-temperature brazed joints. The specimens joined for testing are either an austenitic steel grade X CrNi 189 and an Ag 40 Cd filler metal on the one hand, or an Ni-base material and a BAu-4 gold filler metal on the other.

The Ag filler metal forms Cu-Ag solid solution during the brazing process, interspersed with α-M_k (Ag-Cd-Cu-Zn) crystals as a third phase, / 53 /.

The Au filler metal, on the other hand, consists predominantly of α-solid solutians as the matrix, / 54 /, interspersed with Au- and Ni-enriched solid solutions.

The different structures form strong corrosion elements under the effect of electrolytes which result in the complete dissolution of certain particles, refer to Fig. 30. Strong attack is found especially on the base metal and the transition between filler metal and base metal, / 55 /. The filler metal inclusion which can be seen in the top part of this Fig. has an anodic effect and protects the adjacent base metal. The filler metal, too, is highly destroyed after this test of only 145 hours duration. The Ni-base alloy joined by the gold filler metal, on the other hand, does not show any strong attack either of the base metal or of the filler metal. Here the attack is directed with preference at the grain boundaries along the diffusion zone of the filler metal, refer to Fig. 31.

When these joints are subjected to fatigue testing, marked differences in fatigue strength are found even at very high test frequency and with this relatively minor damage. These differences increase rapidly at lower frequencies and after longer electrolyte exposure.

5. DETECTION OF DEFECTS

Determinations of the strength of structural elements require, in addition to determining the toughness and strength of the materials, information on the defects (initial crack lengths), Therefore, the non-destructive test procedures taken into consideration must satisfy the requirement of identifying the critical defect sizes established on the basis of fracture mechanics. Of special significance for an estimate of hazards due to defects are the orientation, type and geometry of the defect, especially in joints.

In addition to surface test procedures it es especially the X-ray structure and the ultrasonic testing whose application is standardised to a large degree which may be taken into consideration, / 56, 57 /. The defects identified by means of ultrasonic testing or X-ray testing are then reduced to highly simplified basic geometric shapes which are then used for the fracture mechanics evaluation, refer to Fig. 32.

The application range of these procedures is determined by their physical principles. Thus, magnetic particle, eddy current, dye penetration and electric potential procedures can really be used only to test for surface or near-to-surface defects, but in these situations achieve very high accuracy in the order of 10 μm, / 58 /.

The identification limit for X-ray testing is dependent on the dimensions of the defect in the direction of the radiation. Narrow but extended cracks having an angle of only about 5° to the direction of the radiation have not been found in some welds, although the cracks extended over approximately 10 % of the cross-section area.

Ultrasonic test findings are highly dependent on the test frequency, the oscillator geometry and the angles of incidence in conjunction with the defect geometry. Thus, any defect exposed to the sound waves will generate its own reflection field with strong directional beam characteristics, / 59 /. Therefore, the defect size determined by means of AVG diagrams is sometimes subject to great variation, depending on the test frequency and the direction of the sound waves.

At the present time there are still considerable discrepancies in the evaluation of welding defects on the basis of AVG on the one hand and their effect on the safety of structural components on the other. This becomes apparent from a comparison using the example of fatigue testing of a high-strength steel, refer to Fig. 33. In this study it was difficult to estimate the effect of the defect size determined via ultrasonic testing on the endurance of the component. It is likely that there is a similar effect on fracture toughness.

Based on this aspect of unsatisfactory non-destructive testing methodology, therefore, studies have been made more recently which are aimed at greater resolution for the defect geometry. In addition to improvements in test implementation such as tandem techniques and the like, procedures to influence the sound wave field, for instance by means of focusing transducers, and the use of extremely narrow-band signals of infinitely variable frequency, have great advantages. Especially this last-named procedure is found superior to the conventional technique in testing difficult-to-test materials which include welds subject to high structural noise, where narrow-band testing will yield approximately 300 % better results in terms of defect resolution. Thus, in testing Ti workpieces it is still possible to clearly identify defects which are normally no longer detectable. Fig. 34 shows these conditions for a thicker workpiece. If the depth compensation requiered in conventional techniques to eliminate structural noise isaccomplished, the defect cannot be detected, while in the modified technique it contrasts from the noise by about 9 dB.

Similar results have been achieved in identifying defects in high-temperature brazed joints, in adhesive metal bonds and especially in testing reinforced plastics.

One procedure which is used with special success to test adhesive-bonded components is resonance measurement (Fokker Bond Tester), / 60 /. Two effects can be exploited for this technique: while in large-area adhesive bonds the resonace frequency is displaced as a function of adhesive layer thickness and plate, honeycomb structures show a preference for attenuation dependent on the adhesive bond. This procedure can be used to detect with great sensitivity variations of adhesive layer thickness as well as non-bonded areas on large components. Systematic studies on the resolution of smaller defects and on the identification of aging states have not been carried out to date.

In addition to these more or less conventional procedures which also include heat flux measurements which are also used with preference on non-metallic bonds, some other test procedures exist, some of which are still in the laboratory phase. However, at the present time some of these techniques must be eliminated as a result of their low resolution or high test effort involved, such as acoustic holography , / 61 /, or neutron radiography, / 62 / .

On the other hand, optical holography and acoustic emission afford good prospects for defect detection in joints used in aircraft construction.

Holography is especially suitable to determine surface deformations on real structural components, / 63/. These translations can be resolved with an accuracy of approximately 0.1 μm, and at the same time it is possible to test large surfaces. This results in two preferred approaches: on the one hand, defects existing in joints can be identified by forcing deformations onto the joint, for instance via thermic shock, static loading or vibration excitation, / 64/; and, on the other hand, deformation prior to and after the jointing process can be identified to obtain information on existing residual stresses, / 65 /.

Fig. 35 shows the deformation pattern of a metallic sprayed coating under thermal shock. The defect contrasts clearly as a pertubation of the interference pattern from the otherwise rotation-symmetrical band system. The reason is a non-bonded area of nearly 1 cm^2 induced by bad surface treatment. By means of suitable evaluation procedures this interference system can be used to determine the deformation as a function of the wavelength of the light used in each instance.

Fig. 36, on the other hand, shows a bolt welded to the rear of a component. For this purpose the part was exposed prior to and after resistance welding so that the resulting interference bands represent the deformations of the plate caused by the welding process. The high band desity already indicates the great load exposure. Again, suitable evaluation procedures, most of which, however, are still dependent on the use of computers, allow determination of the elongations in the vicinity of the weld.

Acoustic emission analysis is the second procedure with direct application potential for testing joints of high-strength materials, / 66-68 /. Compared to the other, prevously named procedures its advantage is that, being a passive technique, it will yield an indication only when a defect is detected. This means that it cannot detect defect geometries but can detect with great sensitivity the criticality of a defect, independently of its type and orientation. This is possible because even incipient cracks in the order of a few μm will emit sound, some of them even prior to the plastic deformation taking place ahead of a propagating crack. These characteristics lend this technique application potential for both, inspection of large structures and supporting tests in inspections of joints for mechanical and electrochemical resistance.

Fracture mechanics studies of TIG welds of maraging steel grade X 2 NiCoMo 18 85, in conjunction with acoustic emission analysis, allow interpretation of the failure sequence, refer to Fig. 37. This Fig. shows the crack opening sequence under load and the acoustic emission as well as the slope of the curve in the form of a block diagram. The individual slope regions are associated with different crack propagation phases: while the small slope is associated with vold formation in the austenitic components at the grain boundaries, the greater curve slope can be associated with crack propagation through the martensitic region of the structure

Investigations of this kind are already successfully carried out using welded joints of different materials even under normal state, / 69-71 /.

By means of additional analyses a differentiation between the wanted signals and disturbing noise can be achieved. This leads to a very bigly sensitivity, so that the different stages of fracture and the mechanism of failure in welds can be observed. This shall be shown by means of the example of crack propagation in a real weld as a result of welding defects, / 73 /.

Spot welds of high-strength steel grade X 38 CrMoV 5 1 show highly variable fracture forms and defect susceptibility, depending on the heat treatment. During crack propagation itself, high acoustic components are emitted which can be distinguished by their frequency spectra, for instance associated with a certain heat treatment state, refer to Fig. 38. These spectra are recurrent, depending on load (refer to the table in Fig. 38), and can be associated to crack propagation in different structures of the weld, such as nugget structure an the heat-affected zone, by means of metallographic studies, refer to Fig. 39 / 74 /. From these studies it is then possible to derive a failfure model which will make it possible to improve significantly the fracture safety of the weld by means of purpose-oriented modification of the strength behaviour / 73 /.

This technique has also been used successfully for studies on the development of welding defects / 71 /, on the damage profile in adhesive metal bonds and in fibre-reinforced plastics, / 75 /, high-temperature brazed joints / 76 /, involving different base metals.

In particular, this technique could be used to supplement non-destructive testing at regular inspection intervals in that it allows in-flight inspection. At least, this possibility has been indicated in Bailey's studies, / 77 /, who identified in-flight interference noise in his initial studies. Based on this experience it is likely that most noise caused by crack propagation in high-strength materials can be identified clearly.

6. CONCLUSIONS

The mechanical and electrochemical resistances of joints of high-strength materials are considered at present mainly from the point of view of mechanical failure. To understand the toughness and, consequently, the resistance to the extension of defects in the joints, we avail ourselves of the concepts of the mechanics of linear elastic and ductile fracture which may also be referred to the influence of environmental conditions. The same considerations apply to the strength under alternating stress both in monotonic and irregular succession.

As compared to these tests, we mention that the methods concerning the determination of dynamic characteristic values such as the instrumented notched bar impact test are still at the stage of further development. The arrangement of the tests and the measuring technique raise problems which so far do not allow to draw exact conclusions from the phenomena occurring at the top of the crack.

For this reason mainly the methods of the mechanics of linear elastic and ductile fracture for the testing of joints of high-strength material come at present into consideration. For the implementation of this testing it will be essential that the determination of the values be made in the weakest zone and whilst doing so possible defects and the presumable direction of the extension of the defects should be taken into consideration. This especially applies to the geometry of the joint.

Methods of non-destructive testing are used to discover the defects. The recognizability of defects by means of the conventional methods such as X-ray and ultrasonics must be judged with regard to the requirements of the mechanics of fracture. They must be considered as unsatisfactory. In this connection we should mention that there are new methods which are undergoing laboratory tests. The results achieved so far promise to expect an improved determination of the defects.

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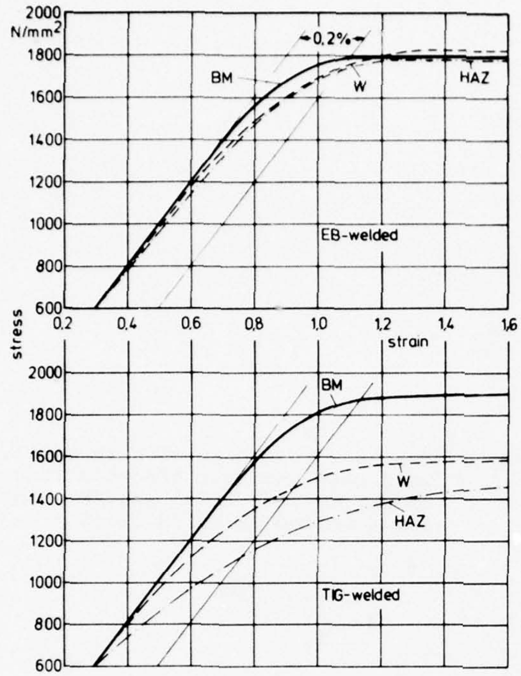


Fig. 1 Stress-strain curves of different parts of a TIG-welded maraging steel (X 2 NiCoMo 18 8 5)

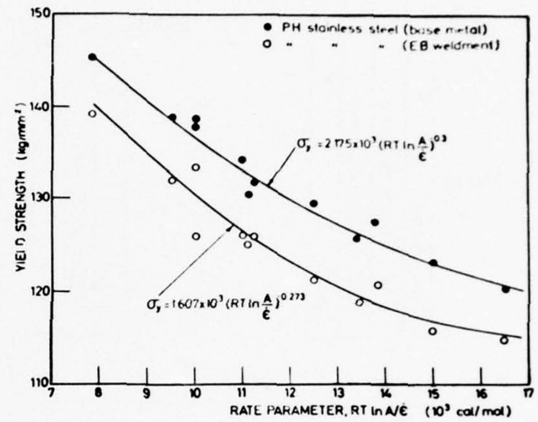


Fig. 2 Yield strength versus load velocity of an EB - welded steel

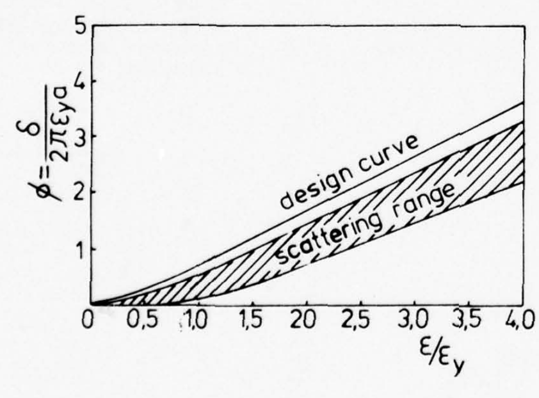


Fig. 3 Schematic diagram of crack opening δ, crack length a and strain ε

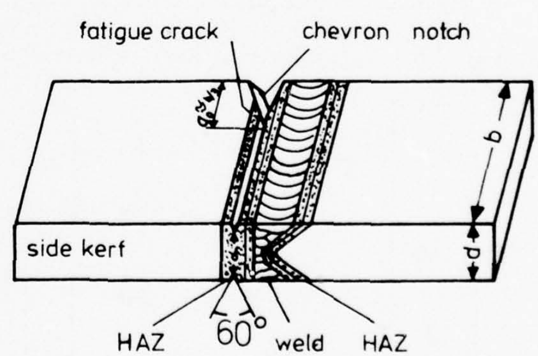


Fig. 4 Specimen with side groovings for fracture toughness testing of the heat affected zones

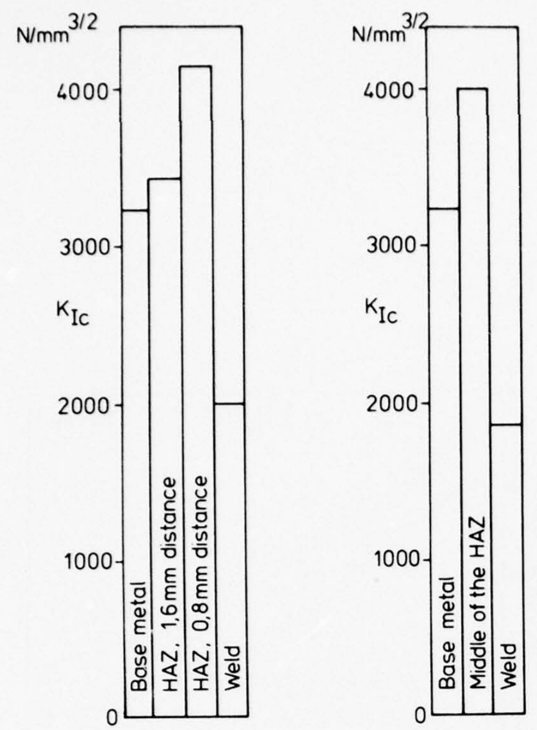


Fig. 5 Fracture toughness of base metal, weld seam and heat affected zone of a TIG (left side) and EB (rigth side) welded maraging steel

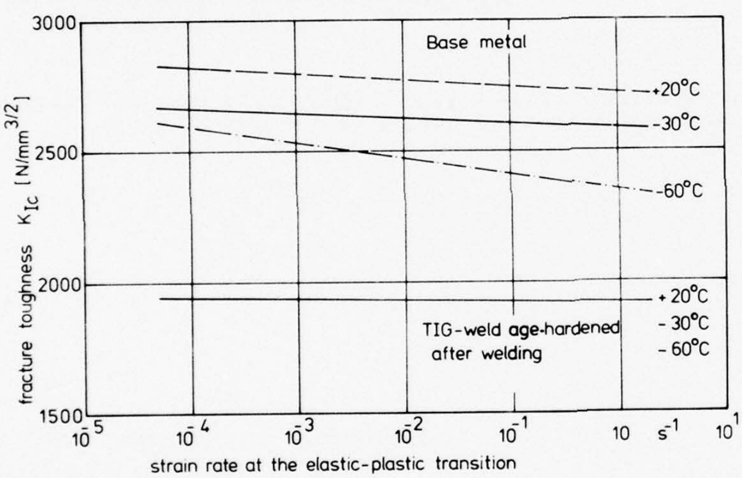


Fig. 6 Fracture toughness of base and weld metal versus testing temperature and load velocity

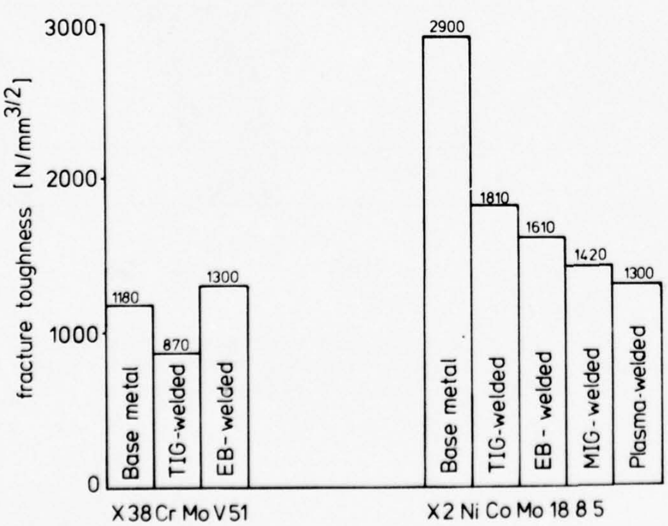


Fig. 7 Fracture toughness of different weldments of two high strength steels

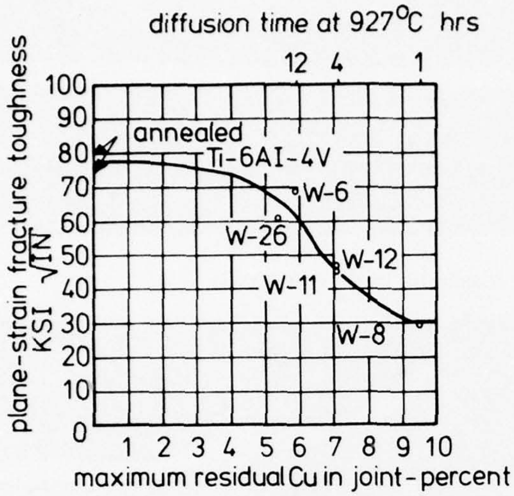


Fig. 8 Influence of residual Cu in brazed joints

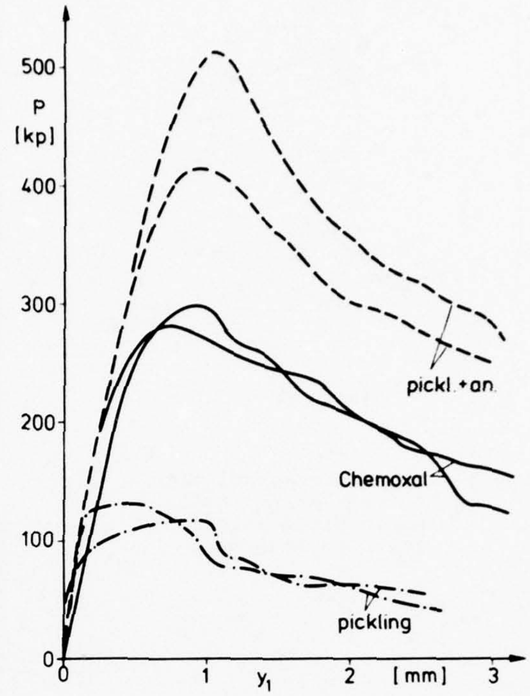


Fig. 9 Crack opening displacement of bonded aluminium
adhesive: modified phenolic resin
(chemoxal: trade name Alu Suisse
pickling: chromatic sulfor acid)

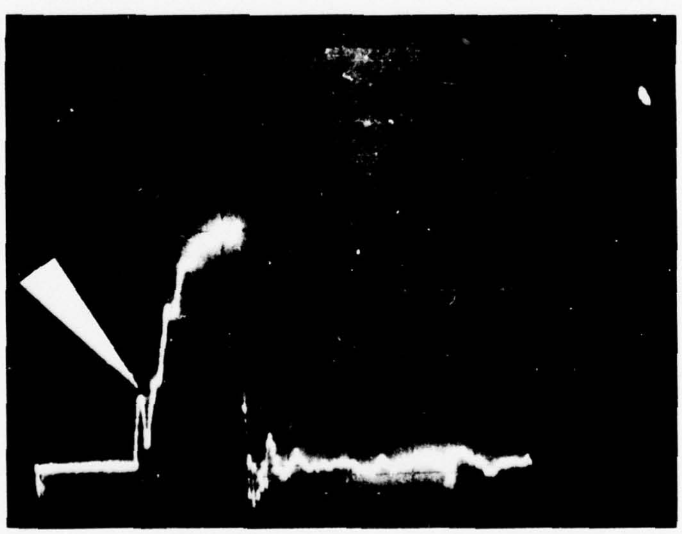


Fig 10 Load time curve of an impact test

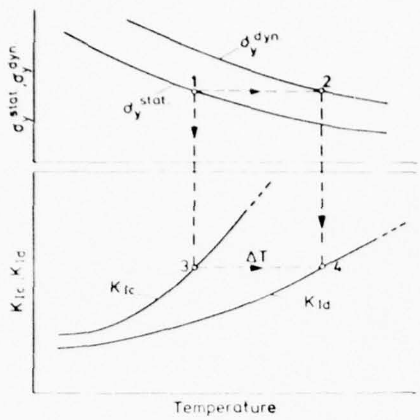


Fig. 11 Schematic correlation between static and dynamic yield stress and fracture toughness

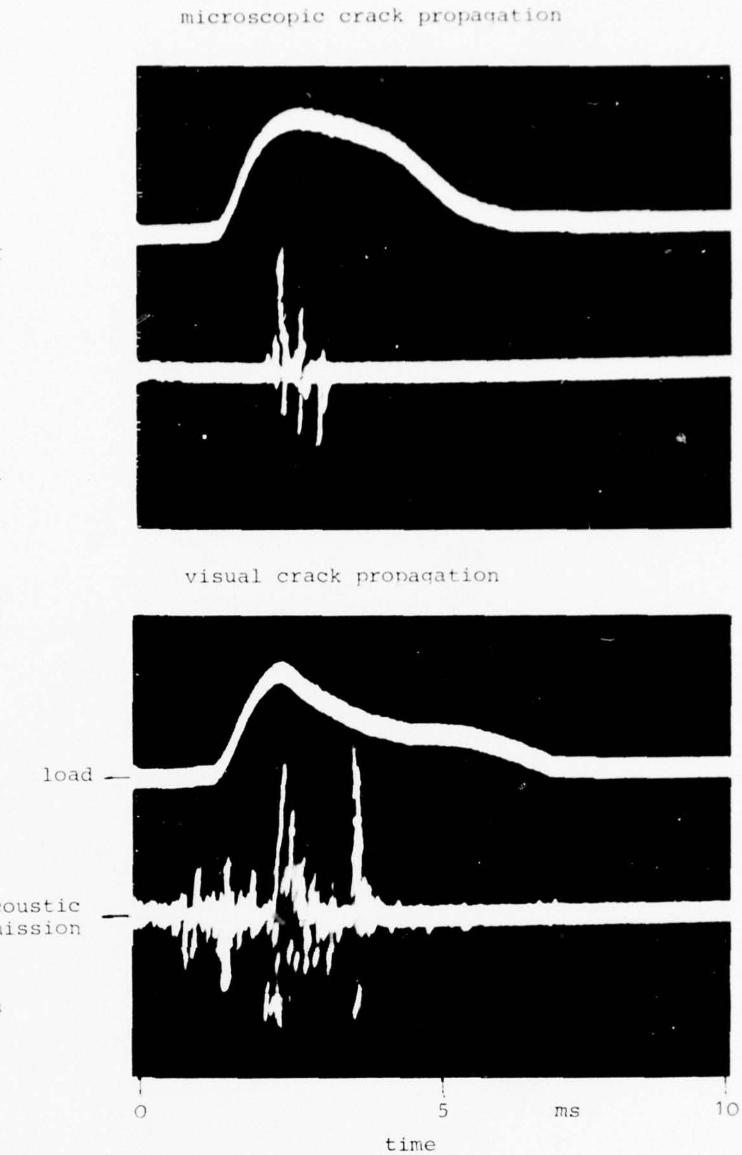


Fig. 12 Load-time curve and acoustic emission of an impact test. Material: high strength low alloy steel

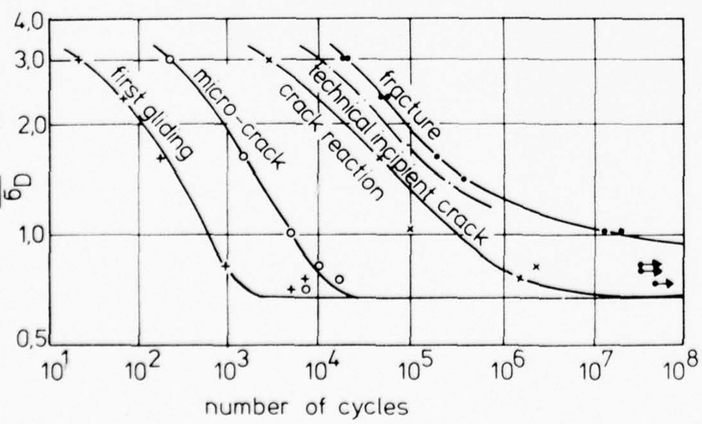


Fig. 13 Mechanisms of failure of an aluminium alloy under fatigue conditions

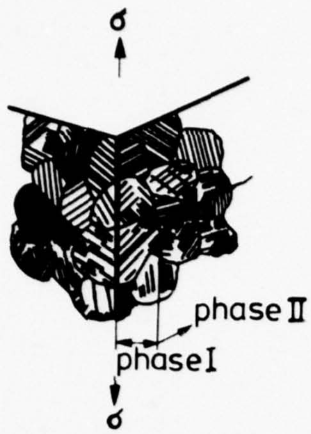


Fig. 14 Crack propagation during fatigue testing

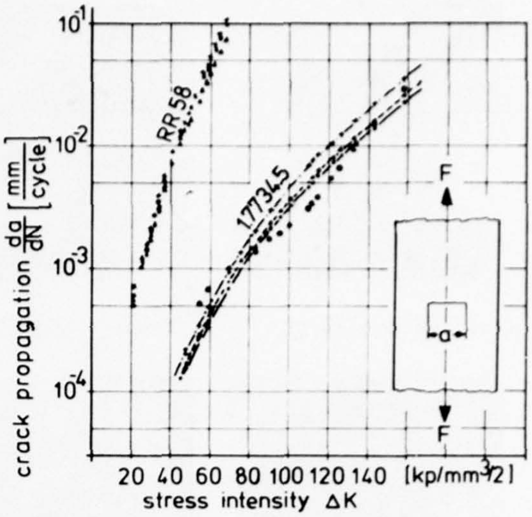


Fig. 15 Crack propagation versus stress intensity under fatigue conditions

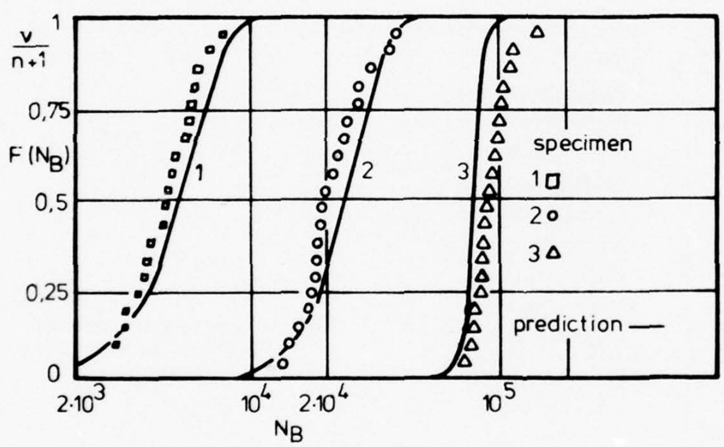


Fig. 16 Comparison between practical results and calculation of the fatigue strength of structures

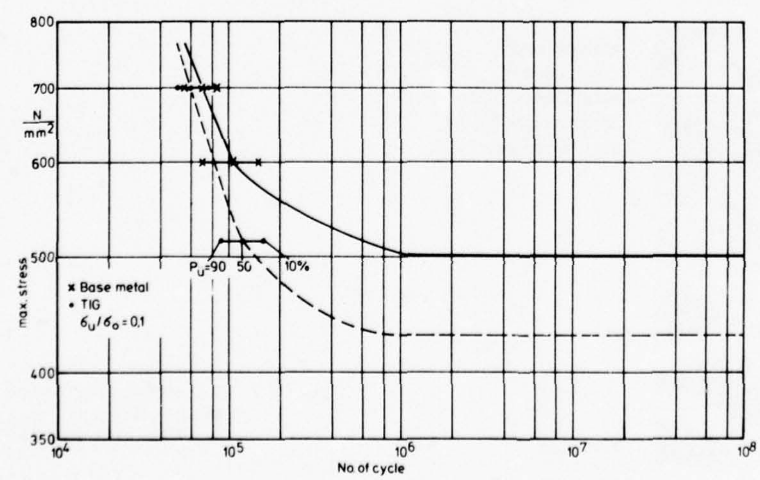
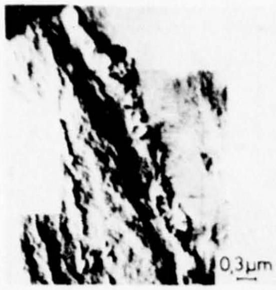
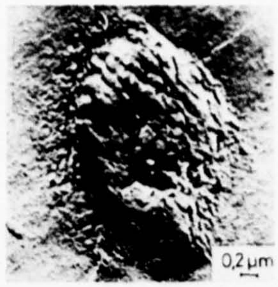


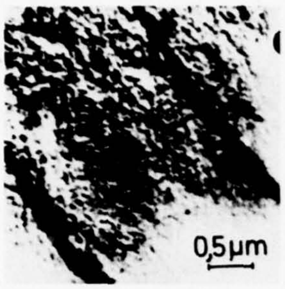
Fig. 17 Fatigue strength of a welded maraging steel



dendrite boundary



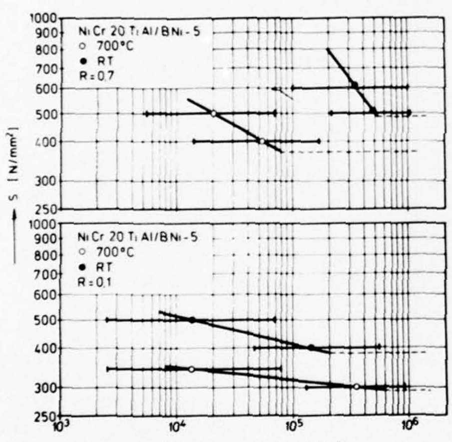
secondary phase



slip stage

slip band

Fig.18 Deformation in the weld metal of a TIG-welded maraging steel. Replica. CAL. R=0,1; σ_o=700 N/mm^2 N_c=75.000 cycles; N=20.000 cycles



Brazing temperature: 1190°C

Specimen shape: Roundtensile to DIN 8525

Testing method: variable tension f = 30 Hz

Heat treatment after brazing: 1100°C / 20h/air 710°C / 16 h/air

Fig. 19 Fatigue life of high temperature brazed joints

5 µm

Fatigue test requirements:
Max. stress: 400 N/mm^2
Stress ratio: R = 0,1
Test temperature: RT

Fig. 20 Scanning electron micrograph of a crystal inside the brazed joint

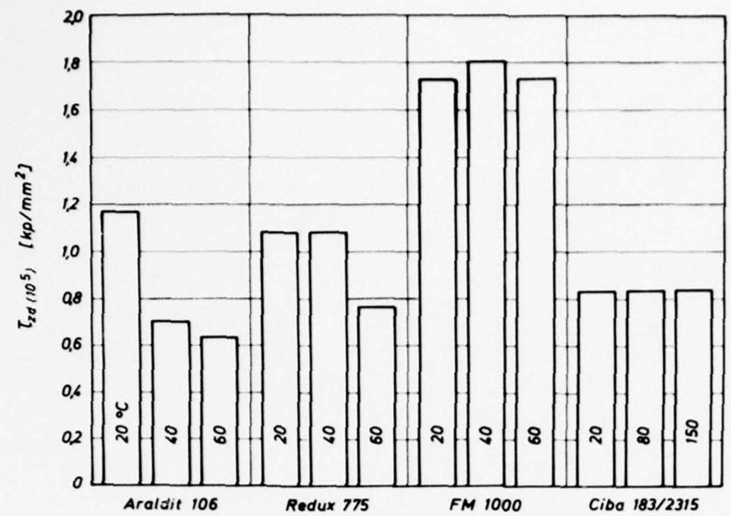


Fig.21 Residual shear strength of aluminium after 10^5 cycles under different testing temperature

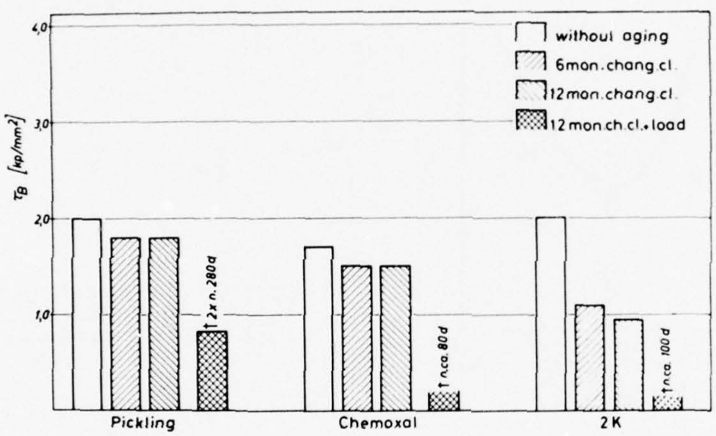


Fig.22 Residual shear strength of aluminium bonds after different aging processes adhesive: polyurethane

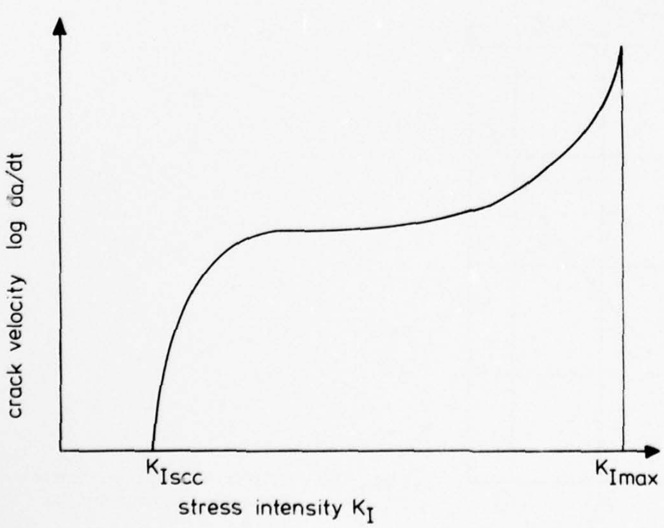


Fig. 23 Schematic representation of crack velocity versus stress intensity

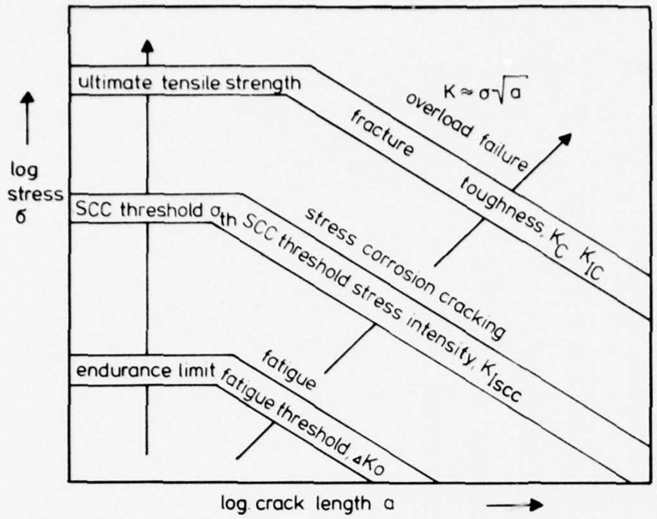


Fig.24 Schematic illustration of the dependence of failure from stress and crack length under fatigue and stress corrosion testing

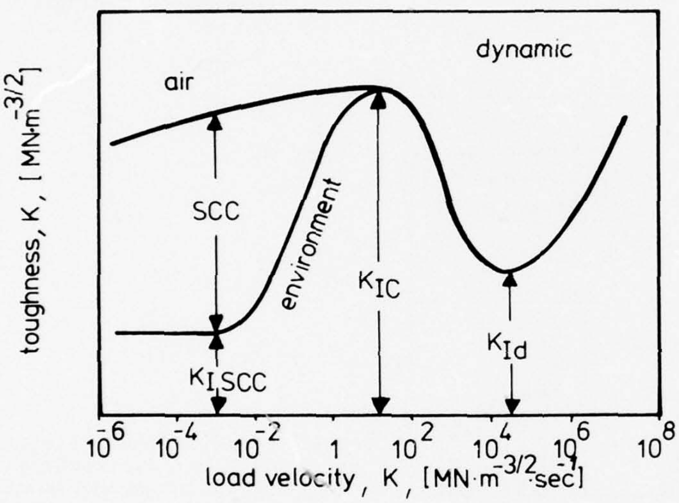


Fig. 25 Fracture toughness of materials in inert and agressive environment

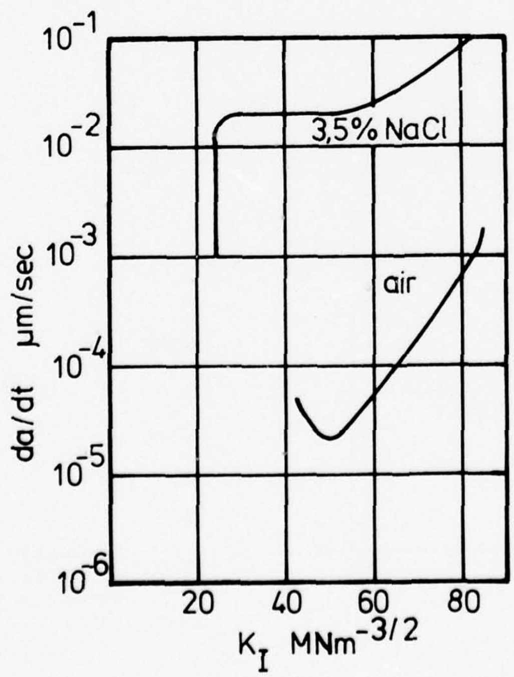


Fig. 26 Crack velocity versus stress intensity of Ti Al 8 Mo 1 V 1

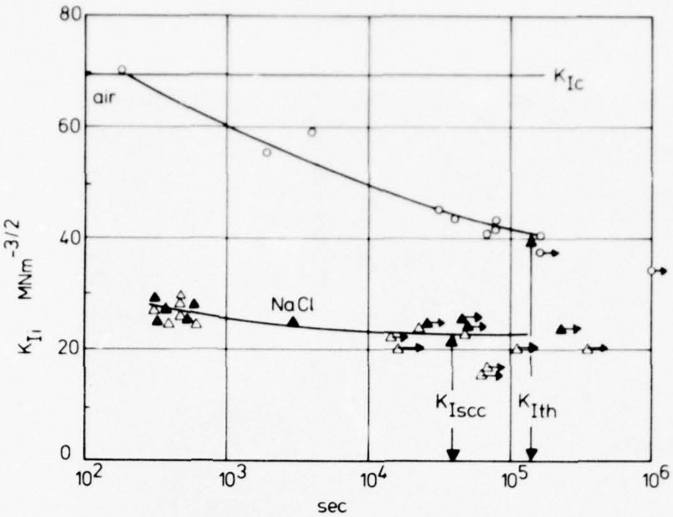
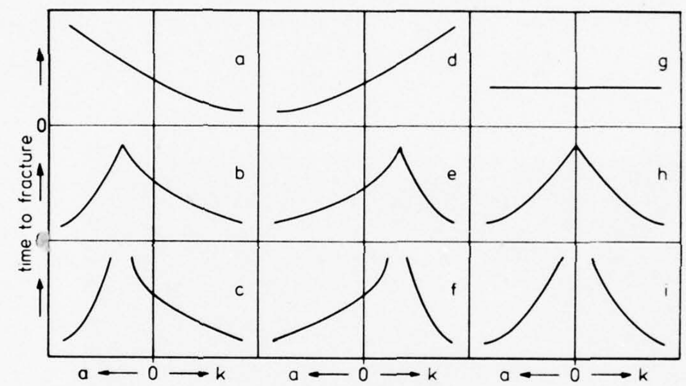


Fig. 27 K_I - log t_b curves of Ti Al 8 Mo 1 V 1

Δ = K_{fmax} = 8,6 MN $m^{-3/2}$

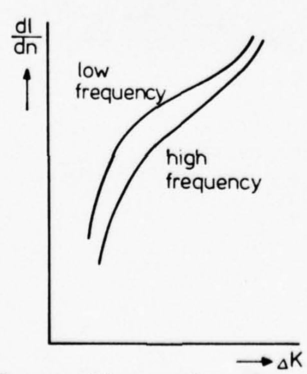
▲ = K_{fmax} = 37,6 MN $m^{-3/2}$



a = anodic polarization
k = cathodic "

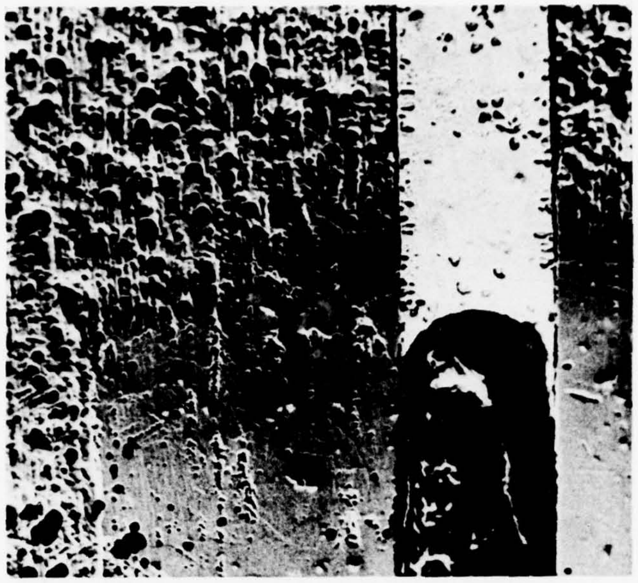
a - c : cathodic corrosion dominant
d - f : anodic " "
g - i : no interpretation

Fig. 28 Determination of corrosion mechanisms

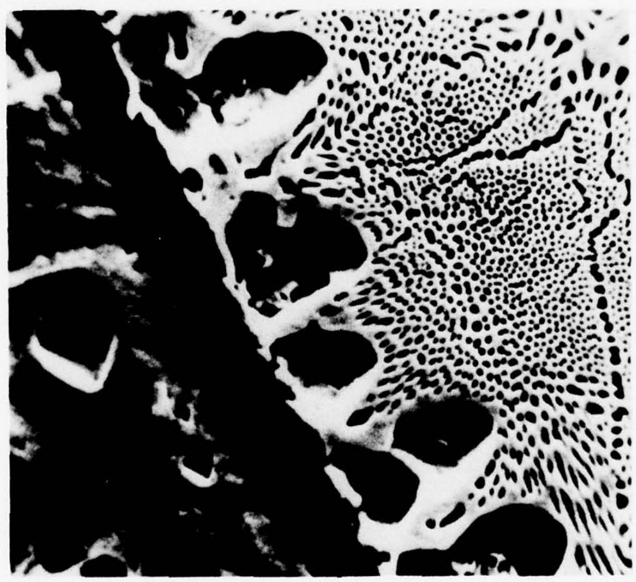


Influence of loading frequency on fatigue crack growth in an aggressive environment

Fig.29 Influence of loading frequency on fatigue crack growth in an agressive environment



16o:1



15oo:1

Fig.3o Scanning electron micrographs of high temperature brazed joints after corrosion attack. (145 h in 5% H_2SO_4)
Base metal: X 5 CrNi 18 9
Filler metal: L-Ag 4o Cd

1500:1

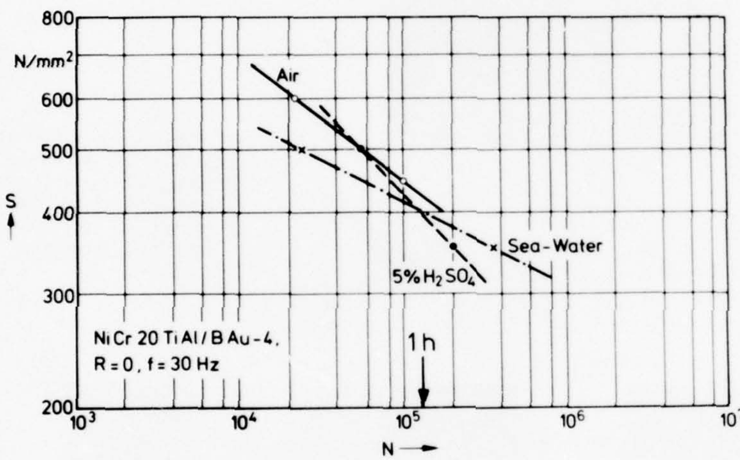


Fig. 31 Corrosion attack on high temperature brazed NiCr 2o TiAl (filler metal:B Au-4) and its influence on fatigue life

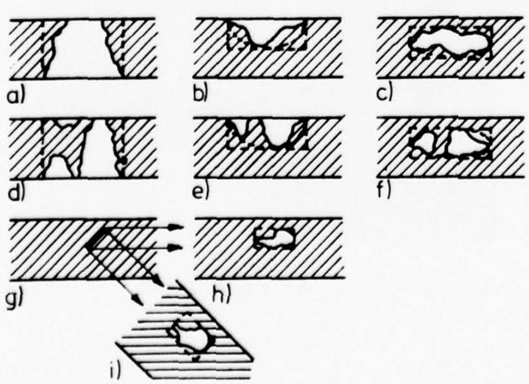


Fig.32 Schematic illustration of the simplification of defects in structures for fracture mechanic calculation

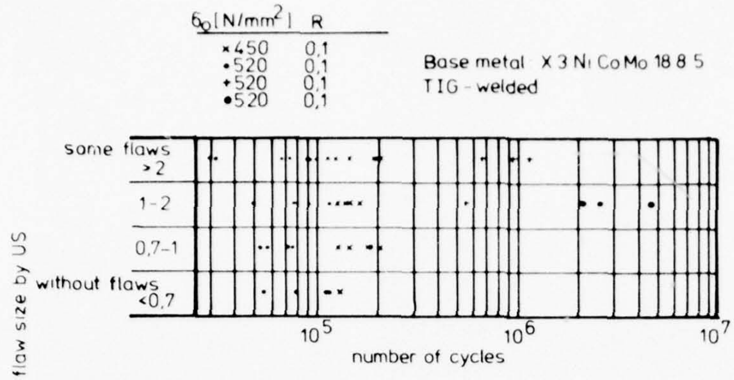


Fig.33 Result of NDT (ultrasonic) of weldments and influence of the detected flaws on fatigue life

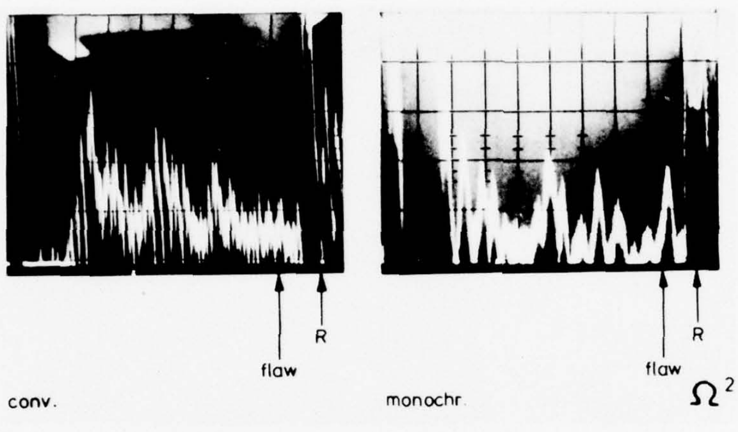


Fig.34 Detection of defects in titanium by a modified ultrasonic technique.
a) conventional technique
b) modified and controlled signals

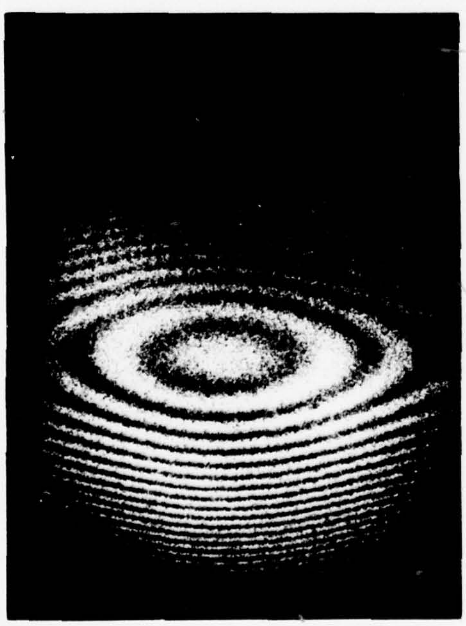


Fig. 35 Hologram of a metal sprayed layer on a high strength steel and the detection of a non bonded part by laser interferometry

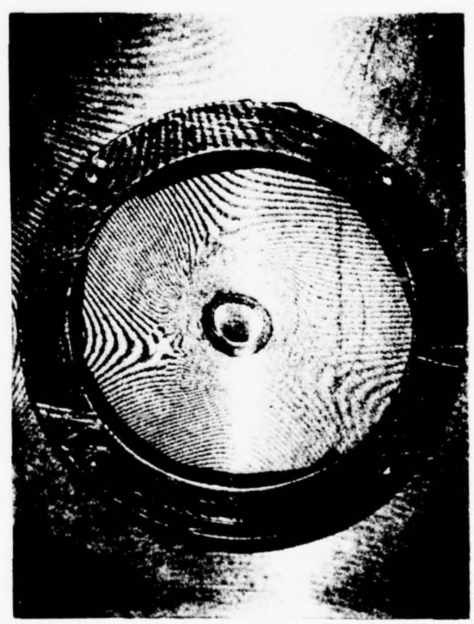


Fig. 36 Residual stresses in a spot welded joint

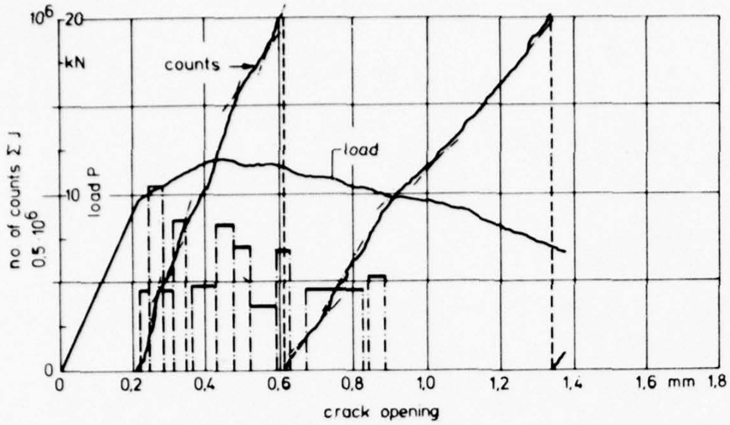
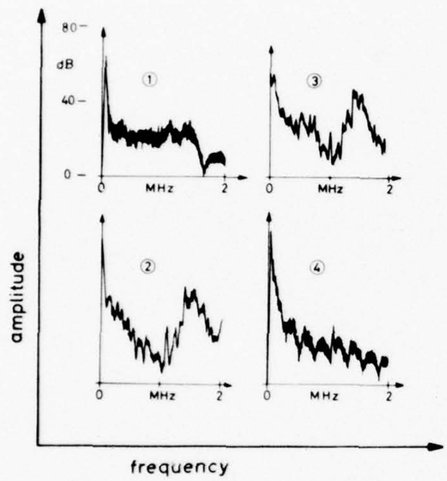


Fig.37 Load - crack opening deflection curve and acoustic emission of a welded maraging steel



shear tensile force	spectra
./. 10 kN	111441111111444 111 44444 1111111 111111111131
./. 15 kN	111 3 1333
./. 17,5 kN	11111111111111111 33333 1423241233 121341132
./. fracture	1111222242 114 11111112134233411 2422342324124232332224 22213314111 1112442231333

Fig. 38 Spectrum analysis of acoustic pulses emitted by crack propagation in a spot weldment of a high strength steel

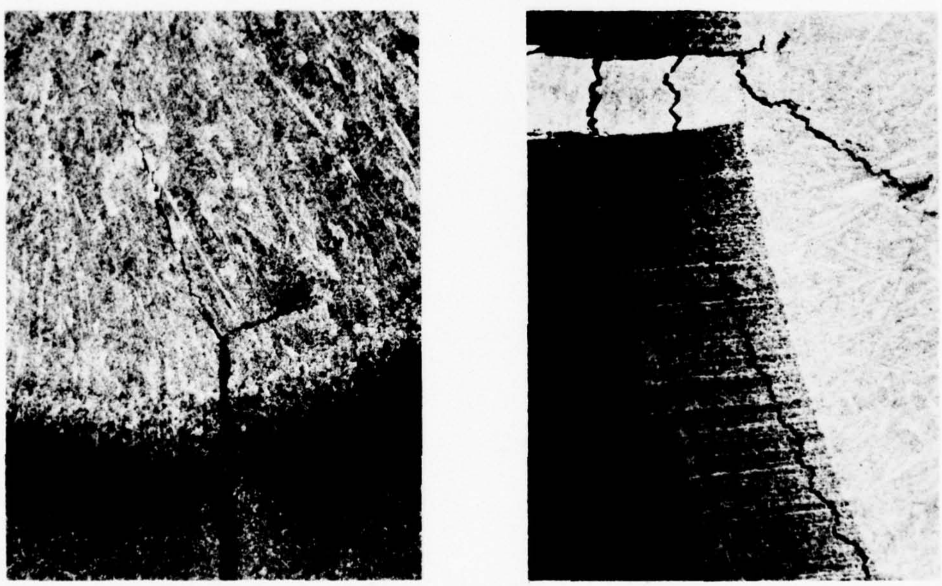


Fig. 39 Crack propagation corresponding to fig. 38
100 : 1

SANDWICH METALLIQUE A AME ONDULEE SOUDE

Améliorations des caractéristiques mécaniques par traitement thermique de relaxation-diffusion

Procédé de contrôle des soudures par thermographie infra-rouge

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RESUME

En raison de leurs qualités de légèreté et de rigidité, l'intérêt des structures sandwich n'est plus à démontrer. Pour les usages à températures moyennement et très élevées, ces matériaux doivent nécessairement être métalliques et être assemblés par brasage ou par soudage.

En France, au cours du développement d'un matériau sandwich à âme ondulée habituellement soudé par points par résistance et commercialisé sous l'appellation NORSIAL, deux techniques particulières ont été expérimentées et évaluées. Ces techniques peuvent aussi être utilisées pour toutes sortes de structures soudées.

La première consiste à faire subir au matériau préalablement soudé par points par résistance, et lorsqu'il est en titane ou alliages de titane, un traitement thermique sous vide qui assure :

- une homogénéisation métallurgique entre le métal de base et les zones affectées par le soudage,
- une relaxation des contraintes dues à ce soudage,
- une augmentation des surfaces de liaison par diffusion à l'état solide sous les seuls efforts des "rétreints" de soudage.

Cette procédure conduit à des améliorations considérables des résistances mécaniques statiques et de fatigue du matériau.

La seconde technique est une méthode de contrôle de la qualité des soudures en cours de fabrication.

Elle consiste à observer la surface du matériau, un court instant après la formation d'un point de soudure, à l'aide d'une caméra infra-rouge associée à un moniteur TV.

La "signature" thermique d'un point de soudure est en rapport étroit avec sa qualité.

Le contrôle peut être effectué visuellement par l'opérateur ou automatiquement par des dispositifs électroniques.

INTRODUCTION

L'usage des structures sandwich dans les constructions aérospatiales s'est généralisé dès les premiers temps de l'aviation. Ces structures permettent en effet de concilier, avec d'autres impératifs, les deux qualités à priori contradictoires que sont la LEGERETE et la RIGIDITE.

En général, une âme légère est utilisée pour assembler des feuilles relativement minces à une distance appréciable l'une de l'autre, apportant ainsi à un panneau de structure, une rigidité considérablement supérieure à celle qu'il aurait si les matériaux étaient réunis en une plaque homogène. Cette propriété mécanique avantageuse sous l'aspect du poids conduit pour des éléments travaillant en compression ou en flexion à la conception d'ensembles structuraux plus légers, moins encombrants et plus simples en diminuant voire en supprimant les cadres, nervures, raidisseurs habituellement nécessaires pour résister au flambage sous charge.

Pour les usages en températures basses ou moyennes, de nombreux produits sont disponibles sous diverses formes généralement assemblées par collage dont la plus courante est à base d'âme en nid d'abeille tant en matières organiques (papier, polyamide, etc ...) que métallique (alliages d'aluminium principalement).

Pour les utilisations en températures plus élevées, l'emploi de métaux de meilleure tenue thermique est nécessaire et les assemblages soudés ou brasés s'imposent.

L'emploi de tels matériaux se justifie particulièrement dans les structures d'avions ou d'engins évoluant à grande vitesse et dans celles des groupes motopropulsifs.

Dans le monde, quelques produits seulement donnent lieu à des fabrications véritablement industrielles ; les architectures sont toutes différentes ainsi d'ailleurs que les techniques d'assemblage qui sont : soit le soudage, soit le brasage, soit le soudo-brasage. Les métaux constitutifs sont très variés, les plus courants sont :

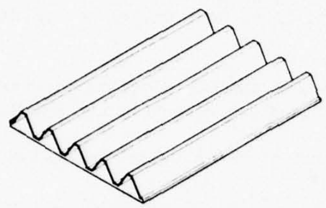
- les aciers inoxydables (AISI Série 300)

- les aciers à traitement de durcissement structural (PH 15-7 Mo, 17-4 PH, ...)
- le titane et les alliages de titane (TA6V4, TA3V2,5,...)
- les superalliages réfractaires à base nickel (Inco 625 et 718, Hastelloy, Waspalloy, René 41, ...)
- les superalliages réfractaires à base cobalt (Haynes 25 et 188, ...)

PRESENTATION DU MATERIAU

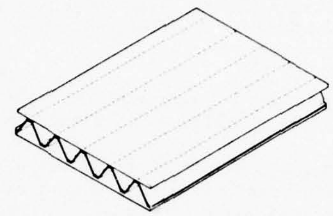
En France, la Société Nationale AEROSPATIALE a développé un matériau sandwich à âme ondulée soudé, dénommé NORSIAL. C'est une structure sandwich constituée de feuilles ondulées assemblées les unes sur les autres pour former un noyau et de feuilles lisses ou "peaux" emprisonnant ce noyau. De très nombreux agencements sont possibles, cependant pour les structures les plus usuelles, les variantes adoptées le plus couramment sont :

- le semi-sandwich composé d'une peau et d'une âme ondulée (figure 1),
- le sandwich simple ondulé, composé de deux peaux encadrant une feuille ondulée (figure 2),
- le sandwich double ondulé, composé des deux mêmes peaux, mais avec un noyau à double ondulation (figure 3),
- le sandwich multi-couche (figure 4).



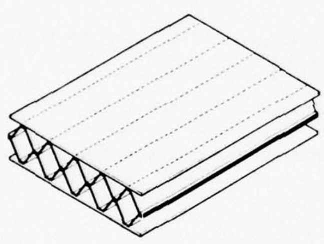
semi- sandwich
semi- sandwich

Figure 1



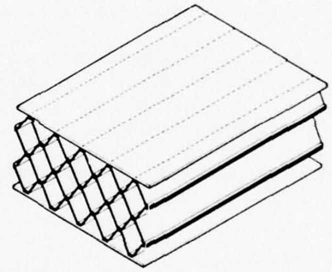
simple ondulé - deux peaux
single corrugated core - two skins

Figure 2



double ondulé - deux peaux
double corrugated core - two skins

Figure 3



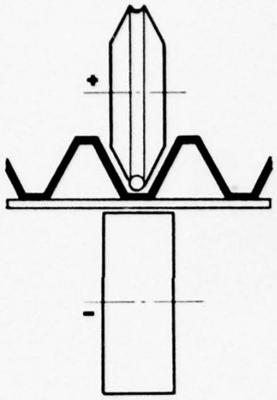
sandwich multicouche
multicore sandwich

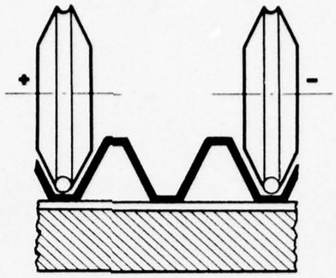
Figure 4

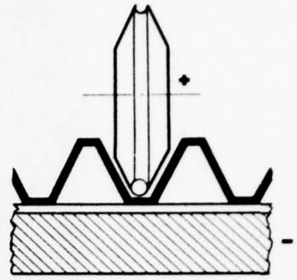
Après l'élaboration des nappes ondulées, l'assemblage des éléments constitutifs du sandwich est généralement réalisé par soudage par résistance à la molette par points ou continu (en chainette) avec ou sans interposition d'éléments conducteurs rigides (mandrins)

De très nombreuses solutions pratiques sont possibles pour effectuer ce soudage, nous en illustrons ci-après quelques unes :

- Figure 5 : soudage d'une peau entre deux molettes, dont une à fil, situées de part et d'autre de la structure sandwich,
- Figure 6 : soudage d'une peau sur table conductrice par deux molettes à fil parallèles,
- Figure 7 : soudage d'une peau sur table conductrice par une molette à fil unique,
- Figure 8 : soudage d'une seconde peau entre deux molettes situées de part et d'autre de la structure sandwich avec interposition d'un mandrin conducteur,
- Figure 9 : soudage d'une seconde peau sur table ou forme conductrice par deux molettes parallèles avec mandrins conducteurs,
- Figure 10 : soudage d'une seconde peau sur table ou forme conductrice par une molette unique et mandrin conducteur.

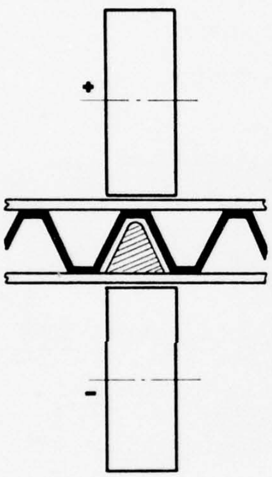


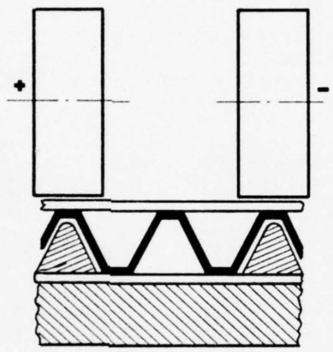


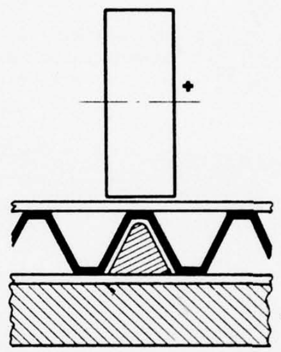


Soudage d'une première peau
Welding of the first skin

Figure 5 Figure 6 Figure 7



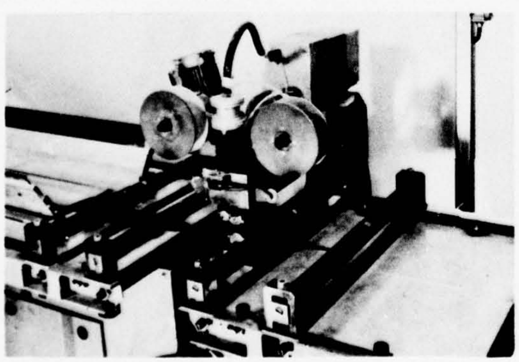




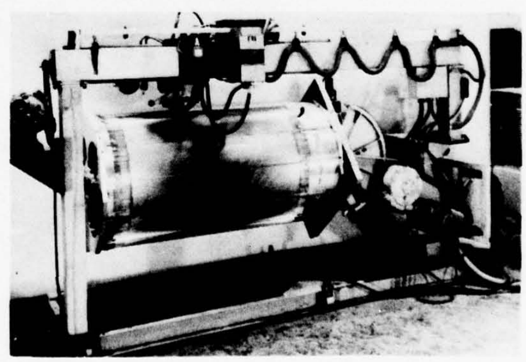
Soudage d'une deuxième peau
Welding of the second skin

Figure 8 Figure 9 Figure 10

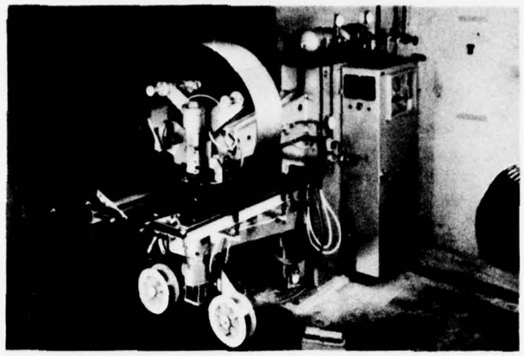
Les figures 11 à 13 illustrent divers types de machines à souder de production.



Machine à souder à plat
Flat welding machine
Figure 11



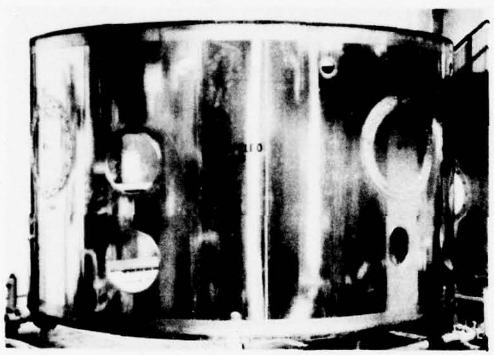
Machine à souder en forme
Welding machine on form
Figure 12



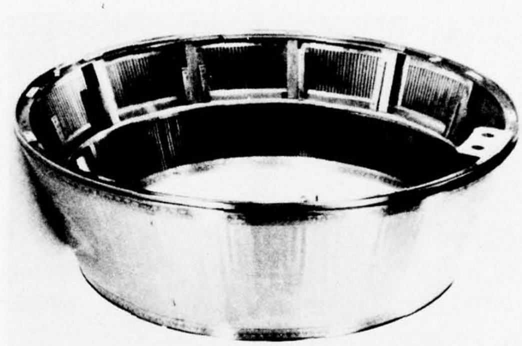
Machine à souder circulaire
Circular welding machine
Figure 13

Quelques exemples de constructions réalisées par cette technologie sandwich soudée sont présentés par les figures 14 à 17 :

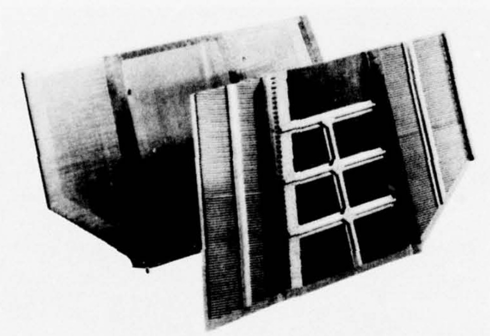
- Figure 14 : Jupe interétage avant du second étage français CORALIE du lanceur spatial européen EUROPA,
- Figure 15 : Jupe arrière du deuxième étage du lanceur spatial DIAMANT,
- Figure 16 : Empennages de missile,
- Figure 17 : Capot de moteur de l'avion de transport militaire TRANSALL.



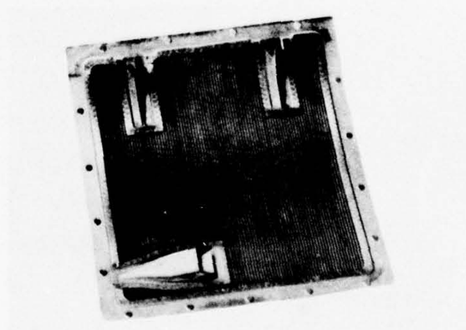
Jupe interétage EUROPA
Interstage skirt for EUROPA
Figure 14



Jupe interétage DIAMANT
Interstage skirt for DIAMANT
Figure 15



Empennages d'engin
Missile stabilisers
Figure 16



Capot moteur de l'avion TRANSALL
Engine cowl for TRANSALL aircraft
Figure 17

AMELIORATIONS DES CARACTERISTIQUES MECANIQUES PAR TRAITEMENT THERMIQUE DE RELAXATION-DIFFUSION

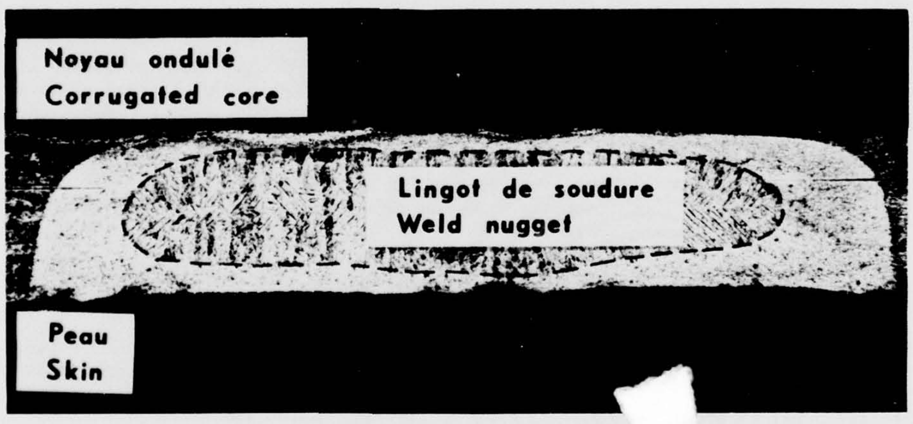
Si le soudage par résistance est en général un moyen d'assemblage qui permet l'obtention de pièces de bonne qualité, quelquefois les métaux utilisés et notamment la majorité des métaux à hautes caractéristiques mécaniques s'adaptent mal à ce mode de liaison. C'est en particulier le cas des alliages de titane dont on connait le comportement médiocre, notamment en résistance à la fatigue, des assemblages soudés par points par résistance. Cet inconvénient est provoqué par des effets métallurgiques dûs aux points de soudure qui ont pour conséquence principale une fragilisation en périphérie des lingots de soudure.

Par contre, on connait aussi l'excellent comportement de ces mêmes assemblages lorsqu'ils peuvent être soudés par diffusion. Il vient donc naturellement à l'esprit de tenter de réaliser l'assemblage des éléments constitutifs du matériau sandwich décrit précédemment, directement par soudage par diffusion. Malheureusement s'il est possible de pratiquer facilement ce type de soudage sur des pièces massives et même d'obtenir des échantillons sandwich de petites dimensions avec du matériel de laboratoire, les solutions industrielles ne présentent pas de garanties de qualité suffisantes ou requièrent des investissements de développement et de production de niveau prohibitif.

Aussi, nous avons pensé qu'il pouvait être intéressant d'améliorer les liaisons du matériau sandwich en alliages de titane en combinant le soudage par résistance par points à la molette tel qu'il est habituellement pratiqué et le soudage par diffusion. La technique consiste à faire subir un traitement thermique sous vide (ou sous atmosphère protectrice) aux structures sandwich terminées préalablement assemblées par soudage par résistance ; la pression nécessaire pour une diffusion à l'état solide autour des lingots de soudure par résistance provient uniquement de l'effet de "rétreint" inclus dans ces lingots, sans autre dispositif annexe de pressage.

Les clichés micrographiques des figures 18 à 21 permettent la comparaison métallurgique des assemblages d'une "peau" de revêtement avec une âme ondulée en alliage de titane TA6V4, entre deux lingots de soudure par résistance :

- Figures 18 et 19 : brut de soudage par résistance,
- Figure 20 : après traitement de 2 heures à 850° C sous vide,
- Figure 21 : après traitement de 2 heures à 950° C sous vide.



Brut de soudage par résistance
After resistance spot-welding operation

Figure 18

Figure 19 : Brut de soudage par résistance — After resistance spot-welding operation

Figure 20 : Après traitement de 2 heures à 850°C — After heat-treatment for 2 hours at 850°C

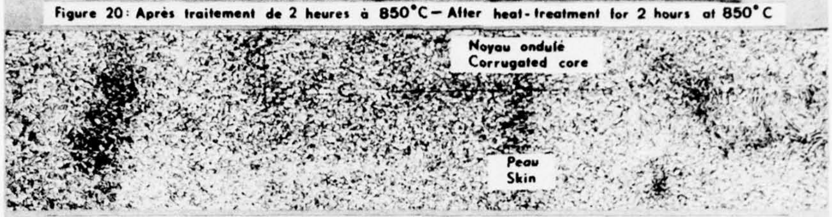


Figure 21 : Après traitement de 2 heures à 950°C — After heat-treatment for 2 hours at 950°C

Les figures 18 et 19 relatives à un état "brut de soudage par résistance" montrent nettement les diverses zones principales :

- les lingots de soudure proprement dits, à structure fortement dentritique,
- les zones périphériques aux lingots de soudure affectées thermiquement par le soudage,
- la zone intermédiaire entre les points de soudure qui laisse apparaître une structure de laminage inhérente à ces clinquants de faibles épaisseurs.

On constate que le traitement thermique provoque progressivement une homogénéisation métallurgique du lingot de soudure, de la zone affectée thermiquement par le soudage par résistance et du métal non affecté. Par ailleurs, l'énergie d'activation, produite par la température élevée procure une mobilité suffisante aux atomes pour traverser le plan de joint séparant le revêtement du noyau ondulé ; la jonction peau-ondulé est favorisée par une coalescence et l'apparition de grains métalliques à la place de l'interface initial, les surfaces de liaison sont considérablement accrues et les entailles en extrêmités de lingots de soudure sont supprimées (leur positionnement dans une zone fragile avait un effet extrêmement néfaste sur les résistances mécaniques, notamment en fatigue).

On constate également, qu'à partir de 850° C,la structure de laminage d'origine s'atténue et qu'à partir de 950° C une structure de recuit à plus gros grain se généralise.

Des filiations de microdureté sous faibles charges (figure 22) confirment qu'après les traitements thermiques sous vide, nous sommes en présence d'une structure recristallisée de recuit apportant :

- une homogénéisation entre le métal de base et les zones affectées thermiquement par le soudage par résistance et notamment un adoucissement des zones corticales aux lingots de soudure originellement dures et fragiles,
- une libération des contraintes dues au soudage.

D'autres essais de qualification, par ailleurs couramment pratiqués en production, ont été entrepris ; ils consistent à mesurer la résistance à l'éclatement par surpression hydraulique interne. Ces essais ont été effectués sur des éprouvettes sandwich à simple couche ondulée (figure 2) en alliage de titane TA6V4 :

- brutes de soudage par résistance,
- traitées 2 heures à 850° C sous vide,
- traitées 2 heures à 900° C sous vide,
- traitées 2 heures à 950° C sous vide.

La pression interne d'éclatement dépend, toutes choses égales par ailleurs, de la surface de liaison entre l'ondulé et les peaux ; il est évident que si la surface augmente, il en sera de même de la pression d'éclatement. Cependant, les lingots de soudure ne sont pas seulement sollicités en traction pure, mais sont plutôt soumis à des efforts combinés, aussi, ce mode de sollicitation n'admet-il que difficilement des liaisons fragiles.

Cet essai peut donc renseigner sur l'évolution de l'assemblage, sous deux aspects :

- accroissement des surfaces de liaison,
- degré de fragilité de l'assemblage.

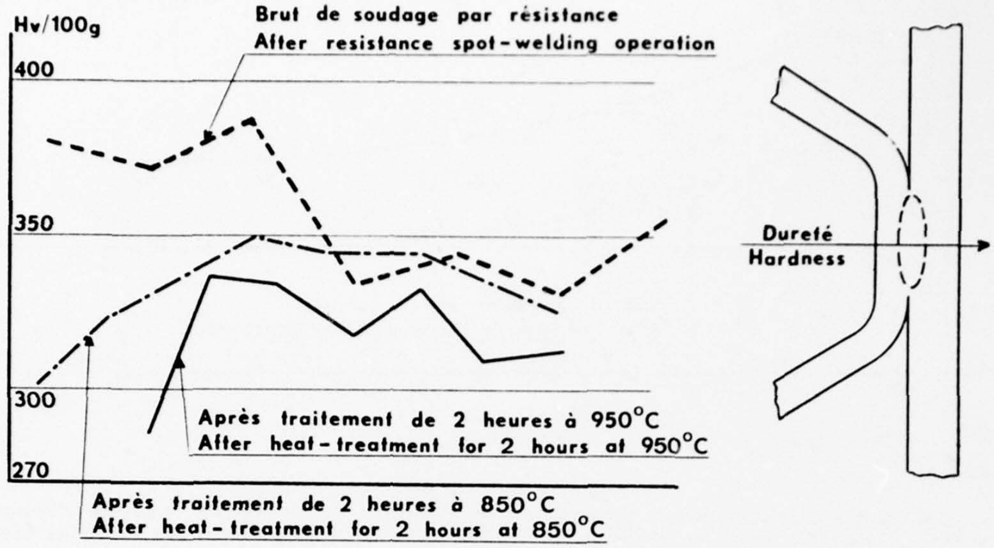


Figure 22

Le tableau ci-après récapitule les pressions d'éclatement de diverses éprouvettes et met en évidence les améliorations apportées par le traitement thermique post-soudage par résistance :

Eprouvettes		Brutes de soudage	traitées 2 h. sous 10^{-5} torr 850° C	traitées 2 h. sous 10^{-5} torr 900° C	traitées 2 h. sous 10^{-5} torr 950° C
Pression d'éclatement (bars)	1er série	80	141		180
		85	119		200
	2ème série	48		140	
				142	
		50		144	

Un autre type d'essais comparatifs a aussi été pratiqué, il correspond à une sollicitation en général très proche des conditions d'utilisation réelles. Il s'agit d'essais de flexion-cisaillement répetée de poutre sous charge centrale.

La figure 23 présente les courbes de Wöehler de résistance en fatigue sous sollicitation de flexion-cisaillement ondulée, respectivement de sandwichs en alliage de titane TA6V4 bruts de soudage par résistance et traités thermiquement 2 heures à 900° C sous vide.

L'intérêt de ce traitement thermique est évident, il accroit de 50 % à 90 % les limites de résistance en fatigue dans la gamme de 10^5 à 10^7 cycles. Ces améliorations sont dues pour une grande part à la suppression par liaison par diffusion de l'effet d'entaille en extrêmités des lingots de soudure par résistance.

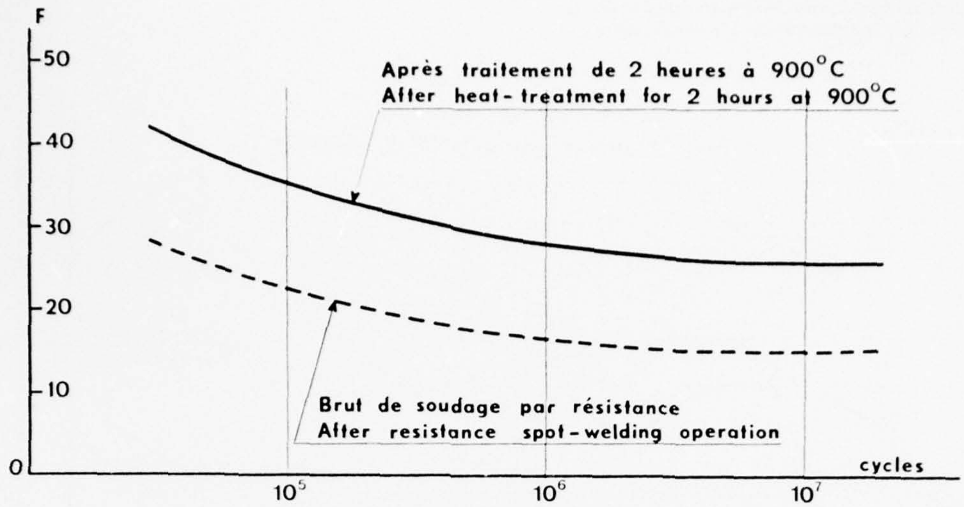
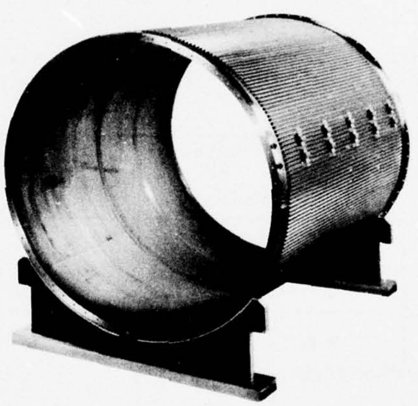


Figure 23

Une application à l'échelle moteur financée par la Direction des Recherches et Moyens d'Essais (France) a été faite sur un canal de rechauffe SNECMA/M 53 qui a subi avec succès des essais au banc (figure 24)



Canal de rechauffe de moteur SNECMA/M 53
Post-combustion duct for SNECMA/M 53 engine
Figure 24

En conclusion, la technique consistant à traiter thermiquement le matériau sandwich NORSIAL en alliages de titane, d'abord soudé par résistance par points à la molette, par exemple pendant 2 heures sous vide à 900° C dans le cas de l'alliage TA6V4, présente des avantages très importants et indéniables quant aux caractéristiques de résistance mécanique du matériau tant sous des sollicitations statiques qu'en fatigue. Ces améliorations sont dues à :

- une homogénéisation métallurgique entre le métal de base et les zones affectées thermiquement par le soudage par résistance,

- une relaxation des contraintes dues à ce soudage,

- une augmentation des surfaces de liaison des revêtements et des noyaux ondulés par diffusion à l'état solide, sous les seuls efforts des "rétreints" de soudage et amenuisant notamment les effets d'entailles aux interfaces.

Cette technique et ses conséquences bénéfiques ont été décrites dans cet exposé dans le cas de l'application à un matériau sandwich particulier, il semble évident qu'elle peut être reconduite à toutes sortes de structures soudées.

PROCEDE DE CONTROLE DES SOUDURES PAR THERMOGRAPHIE INFRA-ROUGE

Le contrôle de l'assemblage des matériaux sandwich est toujours un problème ardu, que ces matériaux soient d'ailleurs collés, brasés ou soudés. Mais en particulier lorsque le matériau sandwich est assemblé par soudure, son contrôle non destructif est un problème, qui jusqu'à ce jour, n'a pas reçu de solution entièrement satisfaisante. Cette lacune est particulièrement ressentie dans l'industrie aérospatiale, qui requiert, pour des raisons de sécurité évidentes, des assurances formelles quant à la qualité des assemblages réalisés.

Les défauts des points de soudure par résistance en général et aussi ceux des structures sandwich à âme ondulée soudées peuvent être de divers types. L'un des plus graves est la non-conformité des dimensions des lingots de soudure à celles qui étaient attendues ; la longueur L, la largeur l, peuvent être inférieures (ou supérieures) à celles prévues, les pénétrations P1 et P2 peuvent être différentes de celles souhaitées (figure 25) ; lorsque l'une d'elles est quasi-nulle, le point est dit "collé" et l'assemblage ne présente pratiquement aucune résistance mécanique.

Le pas de soudage ou la distance entre deux points de soudure consécutifs X doit être également conforme aux spécifications.

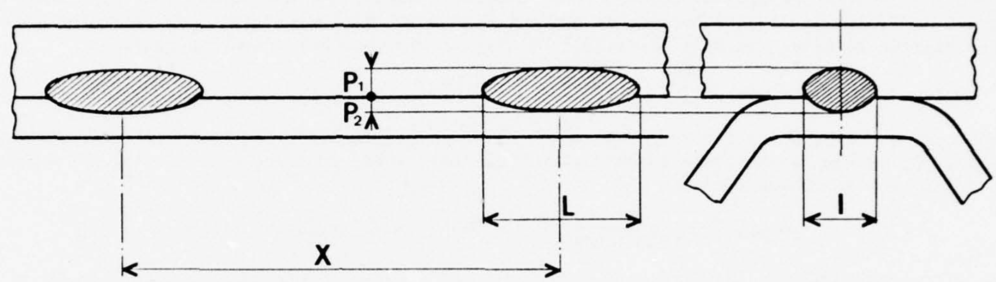


Figure 25

D'autres défauts internes aux points de soudure peuvent aussi apparaître : fissures, retassures, porosités, point "craché" (expulsion de métal fondu) ou brûlé.

Tous ces défauts peuvent avoir des causes extrêmement diverses parmi lesquelles :

- des défaillances de la machine à souder, soit dans la régulation de la tension de soudage, soit dans le comptage du temps pendant lequel est libérée l'énergie de soudage ou des ratés d'allumage du contacteur électronique, soit encore des variations de la pression qui applique la ou les molettes de de soudage contre les éléments à assembler ou encore des vitesses d'avance des molettes de soudage incorrectes, etc ...
- l'état de surface physico-chimique des éléments à assembler,
- l'hétérogénéité des éléments à assembler,
- la qualité des électrodes quant à leur forme, leur dureté, leur géométrie, etc ... ; il faut entendre par électrodes aussi bien les molettes de soudage, que les tables ou formes et les éléments conducteurs intermédiaires et aussi le fil de cuivre qui équipe quelquefois les molettes de soudage (figures 5 à 10),
- la qualité des contacts électriques, par exemple entre les éléments à assembler et la table ou forme conductrice ou encore entre les éléments à assembler et les conducteurs intermédiaires,
- des dérivations de courant intempestives,
- etc ...

Les contrôles des soudures par résistance habituels sont surtout destructifs ; ce sont par exemple des examens macroscopiques ou macrographiques, des essais de résistance mécanique au cisaillement (traction ou torsion), des essais de résistance à l'arrachement ou "déboutonnage" ; tous ces contrôles sont pratiqués soit sur des éprouvettes représentatives de l'assemblage à réaliser, soit par prélèvement de quelques pièces dans un lot important et en conséquence ils ne peuvent garantir absolument toutes les soudures réalisées.

Le contrôle radiographique aux rayons X n'est pas destructif, toutefois il est souvent d'une mise en oeuvre difficile et d'une interprétation délicate dans le cas du soudage par résistance ; il permet de révéler la plupart des défauts internes des points de soudure, mais l'appréciation des dimensions des lingots fondus n'est généralement pas possible et moins encore celle des pénétrations. En outre, ce type de contrôle est obligatoirement pratiqué à postériori, et souvent pour des raisons de commodité et de coût, longtemps après la réalisation des soudures ; dans ce cas, les malfaçons éventuelles peuvent affecter de nombreux ensembles soudés avant qu'elles ne soient détectées.

Il existe d'autres méthodes de contrôles, qui peuvent être pratiquées à postériori, qui utilisent des phénomènes magnétiques ou les propriétés des ultrasons,etc ... ; aucune n'est entièrement sûre et satisfaisante.

Le procédé de contrôle que nous avons expérimenté et évalué et qui va être décrit ci-après, permet de détecter les défauts de soudure de façon non destructive et immédiatement après chaque opération de soudage, qui nous le rappelons se succède à grande cadence, et notamment d'apprécier précisément les volumes des lingots de soudure.

Dans le principe, le procédé consiste à restituer sous la forme d'une image visible graduée en température, les radiations infrarouges émises par chaque point de soudure au cours de son refroidissement, à un instant précis suivant l'impulsion électrique qui a provoqué la fusion.

Dans le cas, par exemple, du soudage d'une structure sandwich à âme ondulée en acier inoxydable, la température de fusion de l'acier inoxydable qui est d'environ 1450° C détermine une émission infrarouge dont le niveau maximum se situe, suivant la formule de Wien, à une longueur d'onde spectrale :

$$\lambda_{max.} = \frac{B}{T} = \frac{2898}{1450+273} \neq 1,7 \ \mu m$$

(B : constante du corps noir, T : température en ° K du corps émissif). En cours de refroidissement, nous nous interesserons aux températures jusqu'à 200° C qui correspondent à une émission infrarouge dont le niveau maximum se situe à la longueur d'onde :

$$\lambda_{max} = \frac{2898}{200 + 273} \neq 6 \ \mu m.$$

Ces deux limites nous ont permis de sélectionner le détecteur de rayonnement infrarouge capable de couvrir l'ensemble spectral de façon à réaliser l'examen avec le maximum de détectivité. Le détecteur le mieux approprié, dans ces longueurs d'ondes correspond à un antimoniure d'indium (InSb).

La figure 26 illustre la façon dont nous avons procédé, par exemple dans les cas de soudage décrits par les figures 7 et 10 dans une vue perpandiculaire à celle de ces figures. La molette de soudage est portée par une tête de soudage qui se déplace dans le sens indiqué par la flèche F. Pour la clarté du croquis, le fil et le transformateur de soudage ne sont pas représentés. Les points de soudure répérés a, b, c, d, et e ont déjà été réalisés, le point f est en cours d'élaboration, le point e en cours d'examen. La restitution des radiations infrarouges de ce point de soudure, sous la forme d'une image visible se fait par l'intermédiaire de la caméra fixée sur la tête de soudage qui capte le flux infrarouge par une optique spéciale et le focalise sur le détecteur (InSb) stabilisé à l'azote liquide. A ce niveau, le rayonnement infrarouge est transformé en signaux électriques qui sont envoyés à une unité de visualisation qui assure le traitement en modulant le faisceau électronique d'un écran cathodique sur lequel se forme l'image.

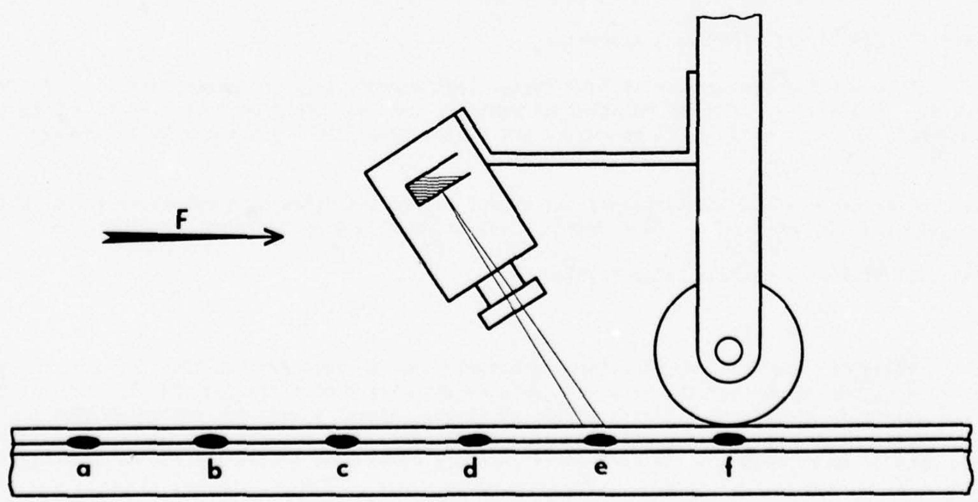


Figure 26

Cette image est une "carte" de niveaux de températures, qui sous réserve d'un étalonnage préalable peut être graduée et chaque zone isotherme chiffrée en température absolue.

La figure 27 reproduit quelques résultats obtenus à l'aide d'une caméra infrarouge de type 750 et d'un moniteur cathodique couleurs de type CM 701 - 750 fabriqués par la Société AGA AKTIELOBAG dans les conditions de soudage et d'observation décrites par la figure 26.

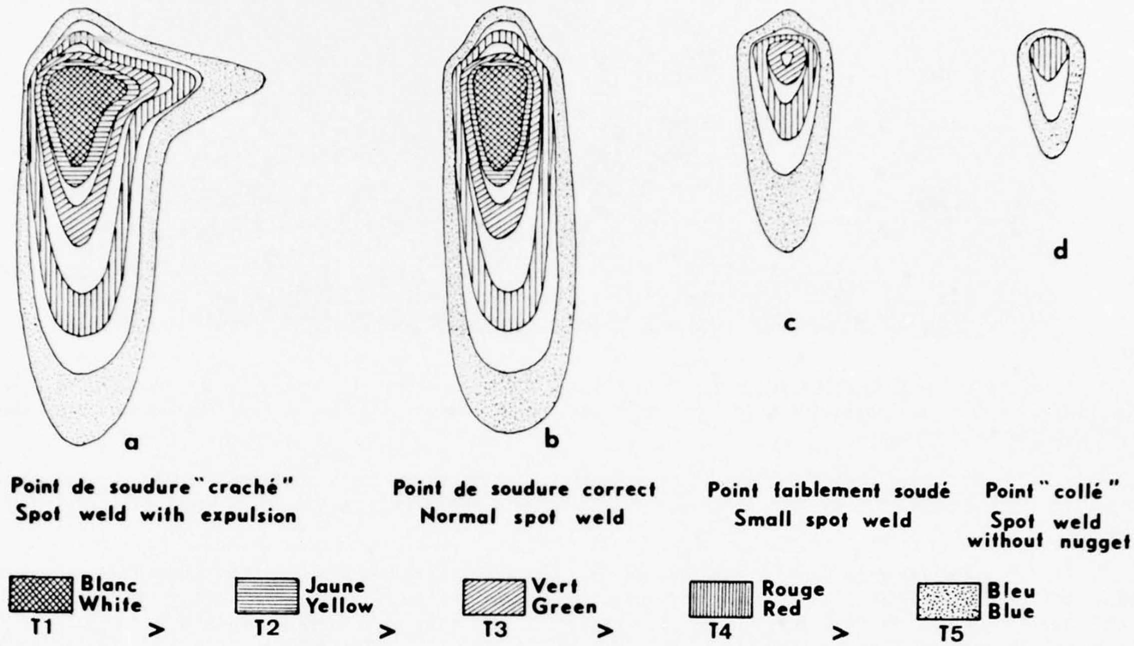


Figure 27

La figure 27b est la "carte" d'isothermes obtenue lorsque les points de soudure sont corrects, c'est-à-dire conformes aux spécifications requises. Les autres cartes d'isothermes sont celles relatives à d'autres points de soudure présentant des défauts caractéristiques. La carte 27c est celle d'un point de soudure faible, c'est-à-dire que les dimensions L, l, P1 et P2 explicitées par la figure 25 sont inférieures aux dimensions souhaitées. Le défaut est parfaitement détecté par la suppression des zones isothermes jaune correspondant à la température T4 et blanche correspondant à la température T5. De plus, les autres zones isothermes bleue (T1), rouge (T2) et verte (T3) ont des formes et des surfaces modifiées de façon évidente par rapport à celles relatives à un point de soudure correct. La carte d'isothermes 27d est celle d'un point de soudure dit "collé", c'est-à-dire que les pénétrations P1 et P2 sont quasi-nulles ; dans ce cas la zone isotherme verte correspondant à la température T3 a disparu et l'image est devenue très petite. La carte d'isothermes 27a est celle d'un point de soudure dit "craché", c'est-à-dire que l'énergie électrique apportée en cours de soudage, ayant été excessive - compte tenu des autres paramètres de soudage - le point de soudure est devenu très gros et a donné lieu à une expulsion de métal fondu. Dans ce cas, les modifications des zones isothermes, par rapport à un point de soudure correct, sont évidentes.

La figure 28 présente la comparaison entre l'image thermique d'un point de soudure réalisé avec une impulsion électrique de durée convenable, à savoir une période soit 0,02 seconde (28a) et un point de soudure réalisé avec une impulsion électrique de durée diminuée de moitié soit 0,01 seconde (28b).

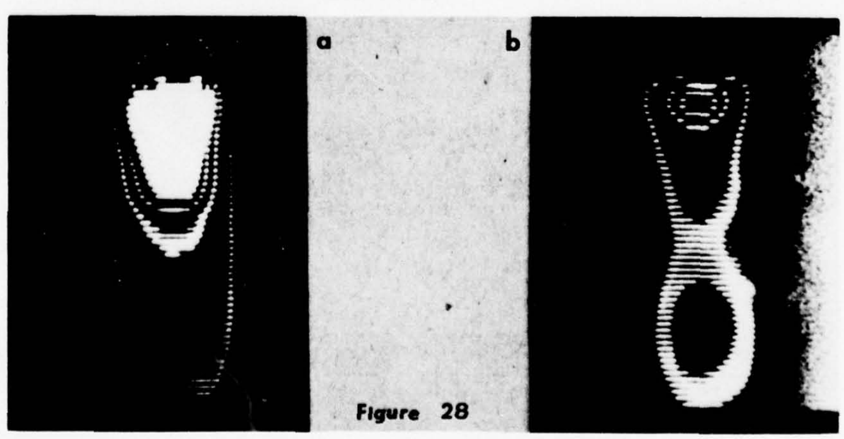


Figure 28

La figure 29 illustre comparativement à une image d'un point de soudure correct (29a), les images obtenues lorsque le contact électrique entre âme ondulée et conducteur intermédiaire est défectueux (29b) ou lorsque le contact entre revêtement et âme ondulée est perturbé (29c)

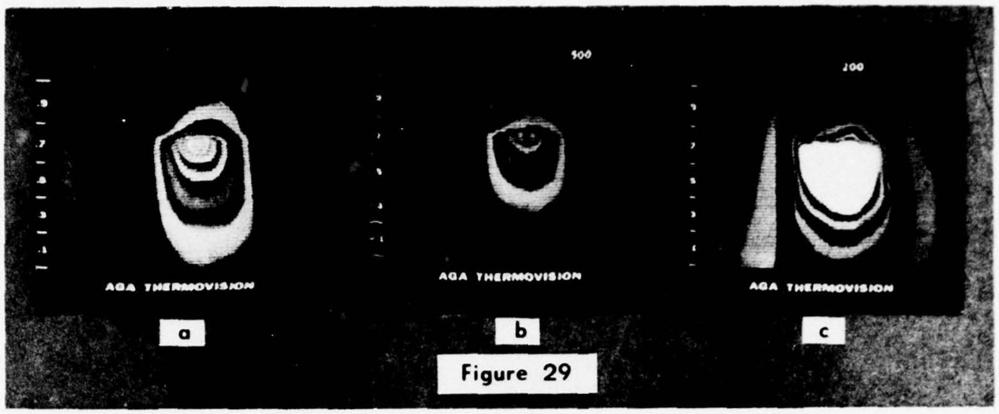


Figure 29

Le contrôle de la qualité de la soudure et de sa concordance exacte avec celle prévue par les spécifications, se fait par comparaison de la "carte" thermique obtenue pour chaque point de soudure avec une carte étalon de référence.

Cette comparaison peut être faite visuellement par l'opérateur de la soudeuse qui est capable d'apprécier, sans autre aide, les défauts les plus importants tels que points "collés" ou "crachés", sur l'écran cathodique.

Pour une analyse plus fine, l'observation peut être facilitée par l'adjonction entre l'écran cathodique et l'oeil de l'observateur, de l'image de la carte étalon de référence tracée sur un support transparent du genre rhodoïd et colorée dans les teintes complémentaires de celles qui apparaissent sur l'écran TV couleur. La figure 30 représente cette disposition dans le cas de cartes isothermes semblables à celle de la figure 27b. Dans le cas où la carte isotherme du point de soudure en cours de contrôle est conforme à celle de référence, la composition des couleurs qui apparaissent sur le tube cathodique et qui sont vues par l'observateur à travers l'écran transparent de teintes complémentaires, déterminent pour l'observateur une "carte" de teinte uniforme de couleur brune, comme il peut être vu sur l'exemple de la figure 31a

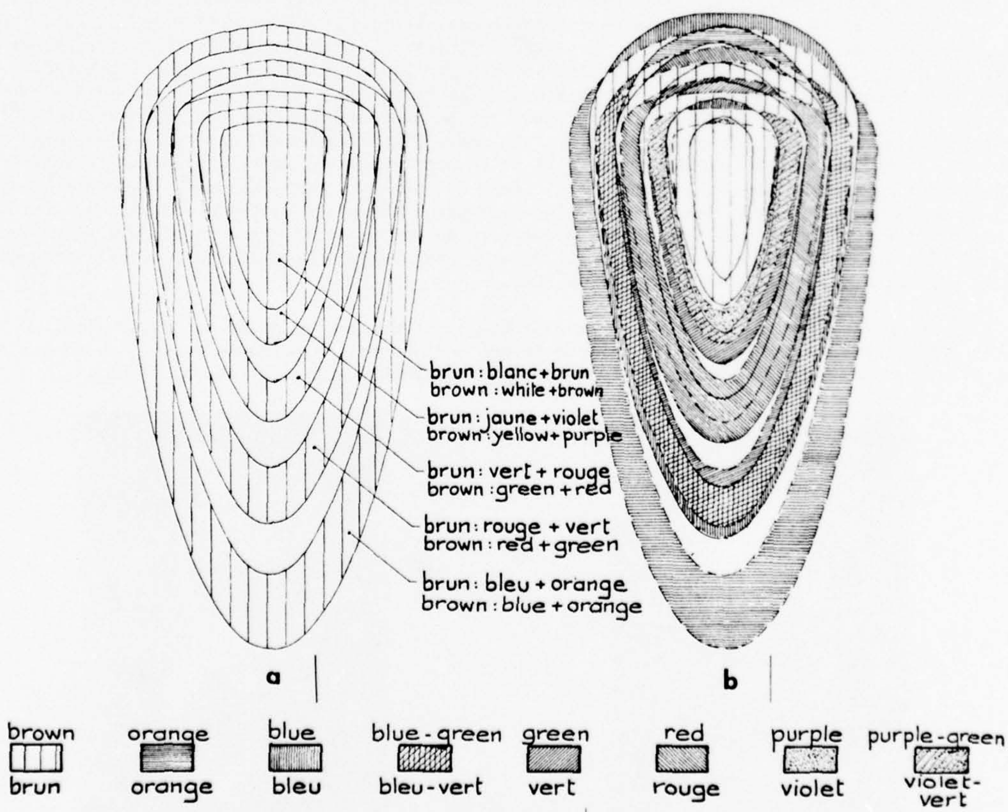


Figure 31

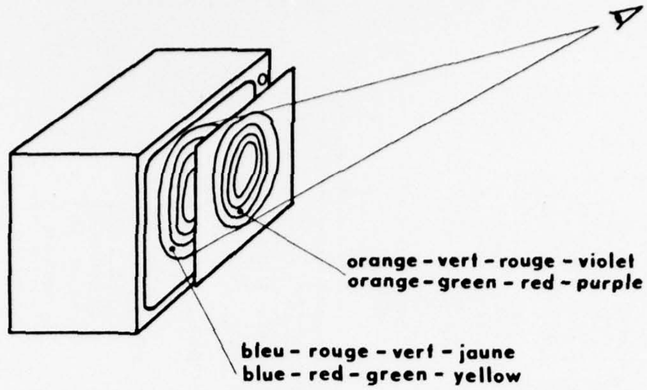


Figure 30

Par contre, dans le cas où la "carte" isotherme du point de soudure en cours de contrôle s'écarte de la carte de référence, l'attention de l'observateur est attirée par des zones fortement colorées jaunes, vertes, rouges, bleues, oranges, violettes qui proviennent soit du tube cathodique à travers les zones non colorées de l'écran intermédiaire et les zones colorées qui ne sont pas de teintes complémentaires, soit de l'écran intermédiaire éclairé par les parties blanches du tube cathodique. La figure 31b fait clairement comprendre ce phénomène révélateur d'un défaut de soudure, où les lignes de contour des zones isothermes sont tracées en trait interrompu pour la carte de référence et en trait continu pour la carte du point de soudure en cours de contrôle.

La comparaison de la "carte" thermique d'un point de soudure avec celle dite étalon d'un point de soudure réputé correct, qui constitue le procédé de contrôle de la qualité peut aussi être faite automatiquement par un appareillage électronique. A titre d'exemple, la figure 33 décrit le schéma de fonctionnement d'un appareillage électronique qui permet d'analyser automatiquement un certain nombre de paramètres géométriques d'une ou de deux ou de plusieurs zones isothermes définies de chaque point de soudure réalisé.

La figure 32 explicite à titre d'exemple, les paramètres géométriques d'une zone isotherme qui sont surveillés par un appareillage de type décrit par la figure 33. Ces paramètres sont : la longueur Lo, la largeur La, la surface S, la symétrie E2 - E1.

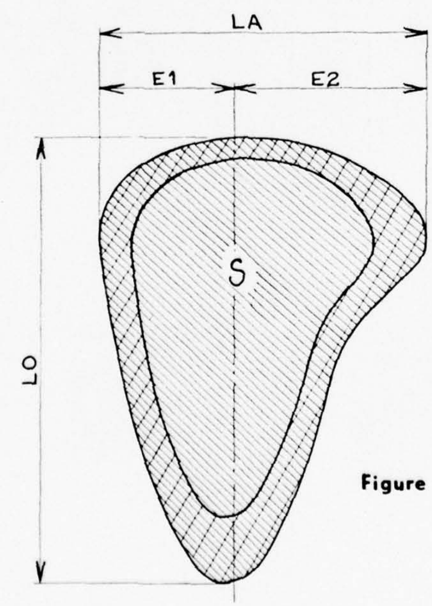


Figure 32

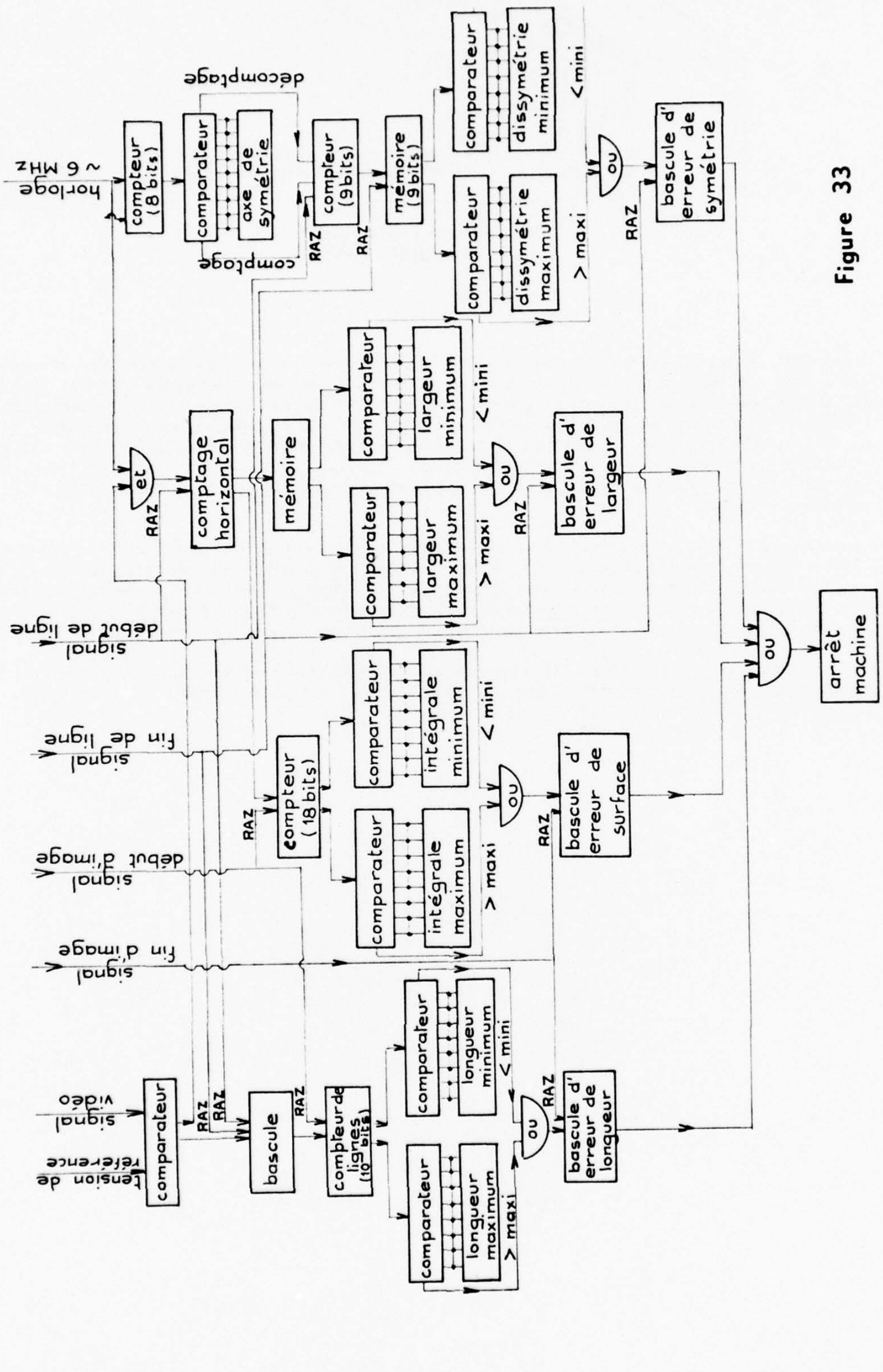


Figure 33

RAZ : Remise à Zéro

Le schéma de fonctionnement de la figure 33 décrit l'appareillage de traitement du signal vidéo, qui permet la surveillance automatique des paramètres précités. Dans le cas d'anomalie d'un des paramètres, dont les limites inférieure et supérieure sont préalablement affichées sur une baie électronique de commande et de surveillance, l'appareillage provoque l'arrêt de la machine à souder.

En conclusion, bien que l'ensemble des possibilités de contrôle de la qualité de soudures par résistance par ce procédé thermographique infrarouge n'ait pas été encore totalement exploré, les résultats que nous avons obtenus dont quelques uns ont été présentés ici démontrent les perspectives de cette méthode. Elle semble particulièrement bien adaptée dans le cas de soudages répétitifs à grande cadence, ce qui est le cas de l'assemblage d'un matériau sandwich à âme ondulée, du fait qu'elle peut être entièrement automatisée, de plus elle n'est pas destructive, et est mise en oeuvre en cours de fabrication et assure donc un auto-contrôle immédiat.

CONCLUSIONS -

Le matériau sandwich métallique à âme ondulée soudé NORSIAL développé par la Société Nationale AEROSPATIALE (France) fait l'objet de recherches continuelles en vue de son amélioration et de l'élargissement de son champ d'application. Au cours de certains de ces travaux, deux techniques ont été expérimentées et évaluées ; une procédure de traitement thermique pratiquée postérieurement au soudage par résistance permet *dans certains cas* des améliorations très sensibles des caractéristiques de résistance mécanique et notamment en fatigue ; un procédé de contrôle par thermographie infrarouge, sensible, fiable, d'un emploi commode, automatisable, non destructif, pratiqué en cours de fabrication et d'un coût modeste, autorise la garantie certaine de la qualité des assemblages par résistance.

Bien que ces deux techniques aient été relatées dans cet exposé dans le cadre particulier d'un matériau sandwich pour lequel nous avons procédé à nos évaluations, il nous semble qu'elles peuvent être aussi mises en oeuvre, moyennant quelques adaptations, pour toutes sortes de structures soudées.

WELDED METAL SANDWICH WITH CORRUGATED CORE

Improvements in mechanical strength characteristics by relaxation-diffusion heat treatment

Method of quality control of spot welds by infra-red thermography

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SUMMARY

Because of their qualities of lightness and rigidity it is not necessary to have to prove the value of sandwich structures. For use at moderate and very high temperatures these products have necessarily to be of metal, assembled by brazing or welding.

In France, during the development of a sandwich material with a spot-resistance-welded corrugated core, produced commercially under the name NORSIAL, two particular techniques were tried and evaluated. These techniques can be used for all other types of welded structures.

The first technique, when titanium or titanium alloys are used, consists in subjecting the material, previously spot welded by the resistance method, to a heat treatment in vacuo, which ensures:

- metallurgical homogeneity between the base metal and the zones affected by the welding,
- relaxation of the welding stresses,
- an increase in the bonding areas by solid state diffusion, under the "hammered" welding forces only.

This process leads to considerable improvement in the fatigue and static mechanical strength of the material.

The second technique is a method of quality control of welds during manufacture.

It consists in observing the surface of the material a brief moment after the formation of a weld point by the use of an infra-red camera, associated with a TV monitor.

The thermal "signature" of a weld point is closely related to its quality.

The control can be effected visually by the operator or automatically by electronic devices.

INTRODUCTION

The use of sandwich structures in aerospace applications has been general practice since the early days of aviation. These structures in fact enable the two apparently contradictory qualities required, LIGHTNESS and RIGIDITY, to be reconciled, together with other essentials.

Generally, a light core is used to assemble the relatively thin sheets, at an appreciable distance from each other, thus providing a panel structure with considerable rigidity, greater than it would have if the materials were combined into a homogeneous plate. This mechanical property, advantageous from the weight viewpoint, for elements loaded in compression or bending, leads to the concept of lighter, less bulky and simpler structural assemblies by the reduction or even elimination of the frames, ribs, stiffeners, usually necessary to prevent buckling under load.

For use at low or moderate temperatures numerous products are available in various forms, usually assembled by adhesive bonding, the most common of which has a honeycomb core of organic material (paper, polyamide, etc.) or metal (mainly aluminium alloys).

For applications at higher temperatures the use of metals with better hot strength is necessary and assembly by welding or brazing is necessary.

The use of such materials is justified especially in structures of aircraft or missiles moving at great speed and in propulsion unit structures.

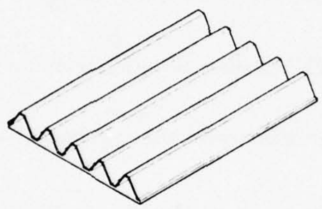
Throughout the world only some products result in truly industrial manufactures. The various modes of construction are just as varied as the assembly techniques – welding, brazing, welding-brazing. The constituent metals are very diverse; the most common are:

- stainless steels (AISI Series 300),
- precipitation hardening structural steels,
- titanium and titanium alloys (TA6V4, TA3V2.5,...),
- the nickel based refractory superalloys (INCO 625 and 718, Hastelloy Waspalloy, Rene 41,...),
- the cobalt based refractory superalloys (Haynes 25 and 188,...).

PRESENTATION OF THE MATERIAL

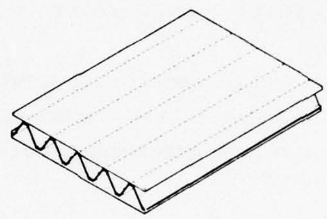
In France the nationalised company Aérospatiale has developed a sandwich material with welded corrugated core, called NORSIAL. This is a sandwich structure formed of corrugated sheets assembled together to form a core and smooth or "skin" sheets containing the core. Numerous arrangements however are possible for the usual structures, the most commonly adopted variants being:

- the semi-sandwich, made up of one skin and a corrugated core (Fig.1),
- the single corrugated sandwich made up of two skins enclosing one corrugated sheet (Fig.2),
- the double corrugated sandwich, made up of the same two skins, but with a double corrugated core (Fig.3),
- the multi-layer sandwich (Fig.4).



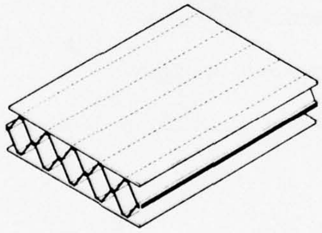
semi- sandwich
semi - sandwich

Figure 1



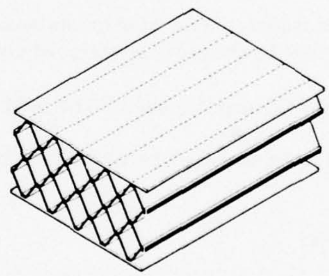
simple ondulé - deux peaux
single corrugated core - two skins

Figure 2



double ondulé – deux peaux
double corrugated core – two skins

Figure 3



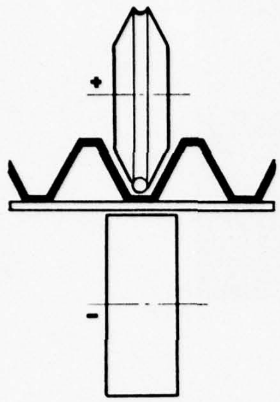
sandwich multicouche
multicore sandwich

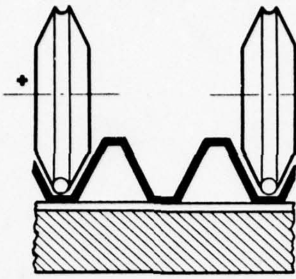
Figure 4

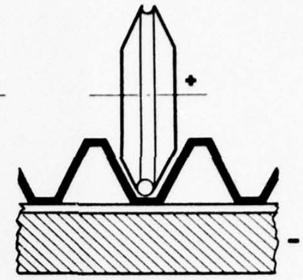
After preparation of the corrugated layers the assembly of the elements forming the sandwich is generally by using roller electrodes in spot welding or seam welding with or without the interposition of rigid conductors.

Very many practical solutions are possible for this welding, we illustrate below a few of these:

- Fig.5: *Welding a skin between two rolls, one with wire, placed on either side of the sandwich structure,*
- Fig.6: Welding a skin on a conducting table with two parallel rolls with wires,
- Fig.7: Welding a skin on a conducting table with one roll with wire,
- Fig.8: Welding a second skin between two rolls placed on either side of the sandwich structure, with interposition of a conducting mandrel,
- Fig.9: Welding a second skin on a conducting table or form with two parallel rolls and conducting mandrels,
- Fig.10: Welding a second skin on a conducting table or form with a single roll and conducting mandrel.

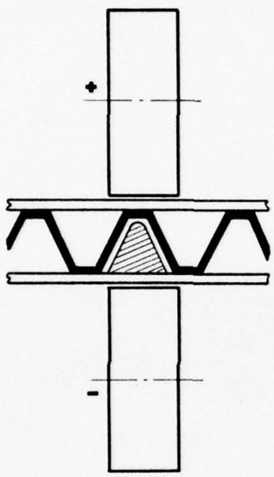


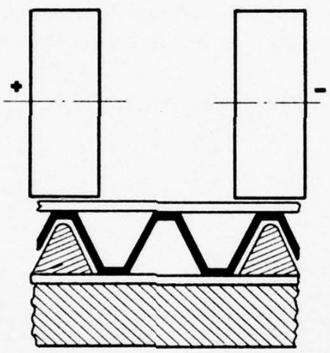


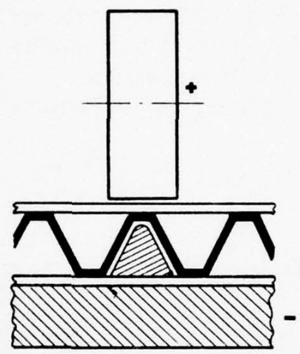


Soudage d'une première peau
Welding of the first skin

Figure 5 Figure 6 Figure 7



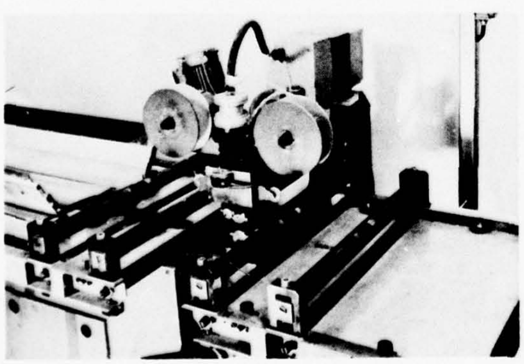




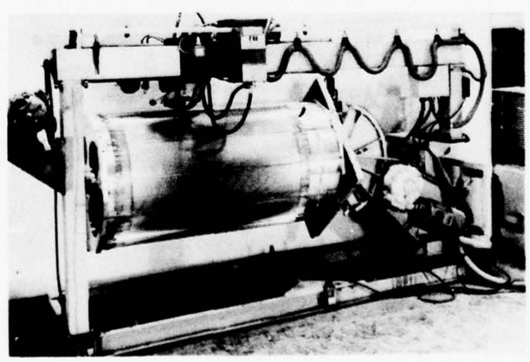
Soudage d'une deuxième peau
Welding of the second skin

Figure 8 Figure 9 Figure 10

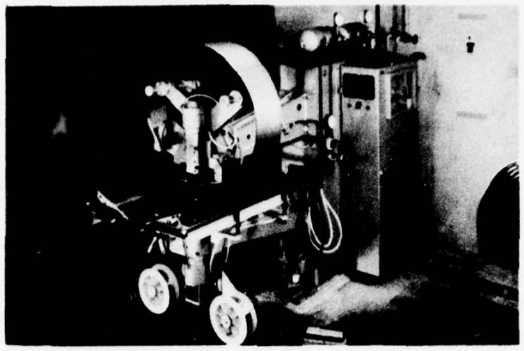
Figures 11 to 13 show various types of production welding machines.



Machine à souder à plat
Flat welding machine
Figure 11



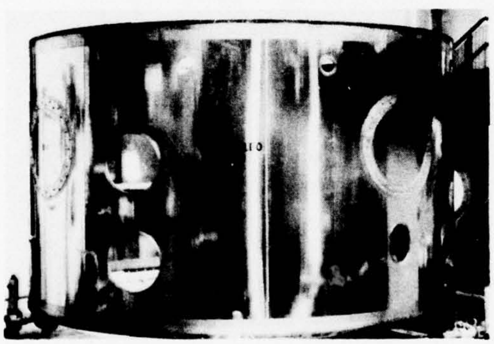
Machine à souder en forme
Welding machine on form
Figure 12



Machine à souder circulaire
Circular welding machine
Figure 13

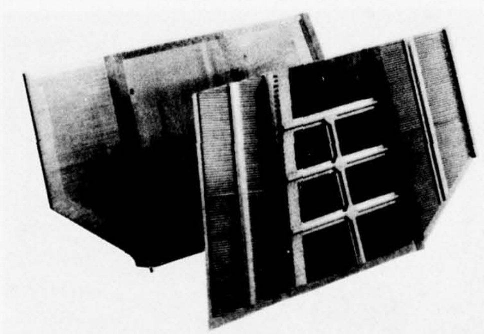
Some examples of construction using this technology of welded sandwich are presented in Figures 14 to 17.

- Fig.14: Front interstage skirt of the French second stage CORALIE of the European space launcher EUROPA,
- Fig.15: Rear skirt of the second stage of the DIAMANT space launcher,
- Fig.16: Missile stabilisers,
- Fig.17: Engine cowl of the military transport aircraft TRANSALL.

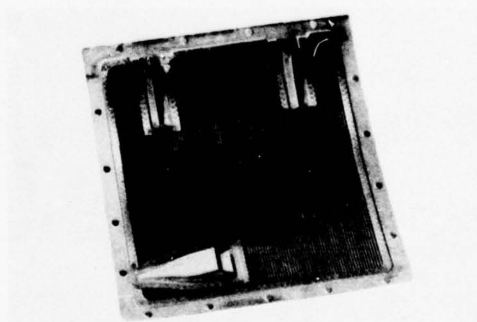


Jupe interétage EUROPA
Interstage skirt for EUROPA
Figure 14

Jupe interétage DIAMANT
Interstage skirt for DIAMANT
Figure 15



Empennages d'engin
Missile stabilisers
Figure 16



Capot moteur de l'avion TRANSALL
Engine cowl for TRANSALL aircraft
Figure 17

IMPROVEMENTS OF THE MECHANICAL CHARACTERISTICS BY RELAXATION-DIFFUSION HEAT TREATMENT

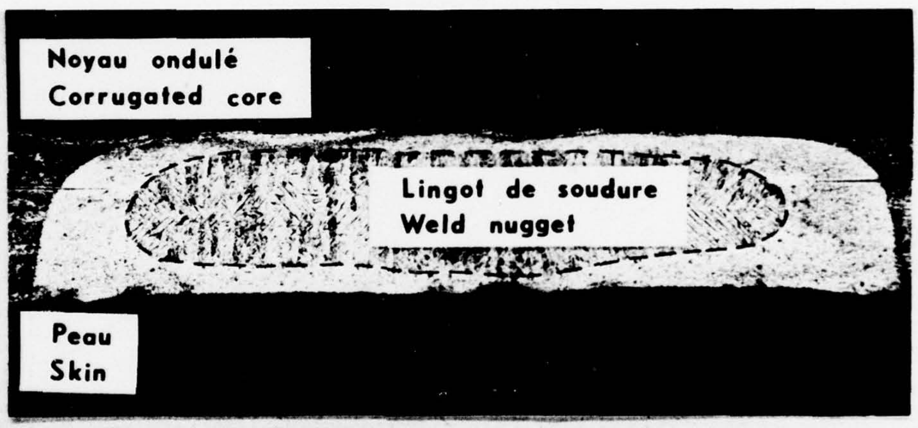
Even if resistance welding is generally a means of assembly enabling good quality parts to be obtained, sometimes the metals used and especially most of the metals of high mechanical quality are not well suited to this method of bonding. This is particularly so for titanium alloys, whose mediocre behaviour, notably in fatigue strength, in spot welded structures, is well known. This disadvantage arises from metallurgical effects, due to weld spots, which result especially in an embrittlement of the periphery of weld nuggets.

On the other hand, the excellent behaviour of these same assemblies is well known when they have been diffusion welded. It thus naturally comes to mind to try to achieve the assembly of constituent elements of the sandwich material described above direct by diffusion welding. Unfortunately, even if it is possible to apply this type of welding easily to massive parts and even to obtain sandwich samples of small dimensions with laboratory equipment, industrial solutions offer no guarantee of adequate quality, or require research and production investments of a prohibitive extent.

Therefore we thought it would be useful to improve the bonds of the titanium alloy sandwich material by combining spot welding with rollers, as commonly practiced, with diffusion welding. The techique consists in subjecting the finished sandwich structures, previously assembled by resistance welding, to heat treatment in vacuo (or under a protective atmosphere). The pressure necessary for solid state diffusion around the resistance welded nuggets *comes solely from the "hammering" effect within these nuggets*, without any other auxiliary pressure device.

The photomicrographs of Figures 18 to 21 allow a comparison of the metallurgical state of the assemblies from a cladding "skin" with a corrugated core of titanium alloy TA6V4, between two resistance welded specimens:

- Figs 18 and 19: Untreated resistance welding,
- Fig.20: After treatment of 2 hours at 850°C in vacuo,
- Fig.21: After treatment for 2 hours at 950°C in vacuo.



Brut de soudage par résistance
After resistance spot-welding operation

Figure 18

The Figures 18 and 19, relating to an "untreated weld" state, show distinctly the various main zones:

- the weld nugget proper, with a strongly dendritic structure,
- the peripheral zones of the weld nugget thermally affected by welding,
- the intermediate zone between the weld spots showing a rolling structure inherent in these thin foils.

It is found that the heat treatment produces a progressive metallurgical uniformity of the actual weld nugget, of the zone affected by the heat of resistance welding and of the unaffected metal. Moreover, the activation energy produced by the high temperature results in sufficient mobility for the atoms to cross the joint plane separating the cladding from the core. The skin/core junction benefits from coalescence and the appearance of metal grains instead of the original interface; the bonding areas are considerably increased and the notches at the ends of the weld nuggets are eliminated (their location in a brittle zone had a deterioratory effect on the mechanical strength, especially in fatigue).

Figure 19 : Brut de soudage par résistance – After resistance spot-welding operation

Figure 20 : Après traitement de 2 heures à 850°C – After heat-treatment for 2 hours at 850°C

Figure 21 : Après traitement de 2 heures à 950°C – After heat-treatment for 2 hours at 950°C

It is also found that as from 850°C the original rolling structure becomes less and as from 950°C a larger grained annealed structure becomes general.

Series of low-load microhardness tests (Fig.22) confirm that after heat treatments in vacuo we have an annealing recrystallised structure conferring:

– homogeneity between the base metal and the zones heat affected by the resistance welding and notably a softening of the cortical zones of the weld nuggets, originally hard and brittle,

– release of the stresses arising from the welding.

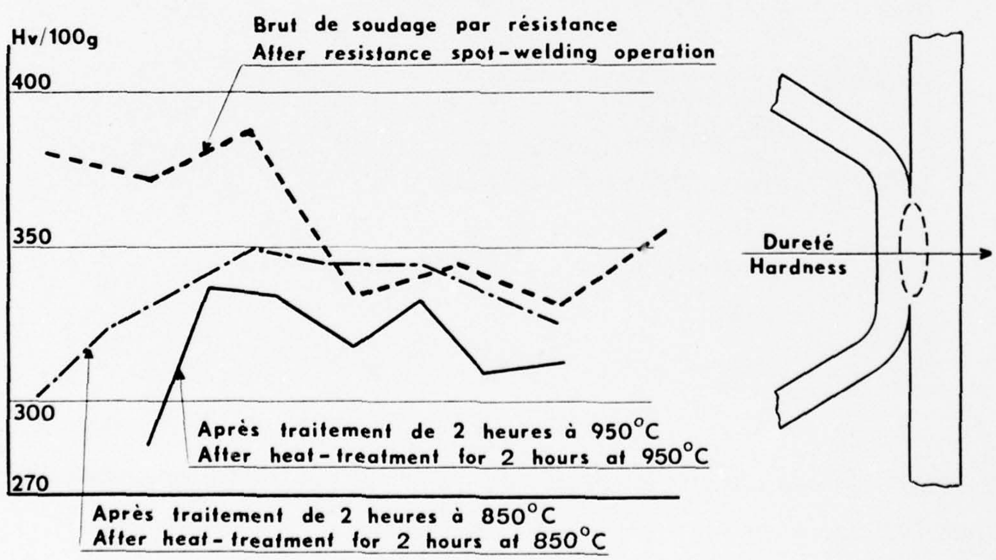


Figure 22

Other qualification tests, currently used in production, have been undertaken. They consist in measuring the resistance to bursting under internal hydraulic pressure. These tests have been made on sandwich test pieces with a single corrugated layer, of titanium alloy TA6V4 (Fig.2):

– untreated resistance welding,
– treated in vacuo 2 hours at 850°C,
– treated in vacuo 2 hours at 900°C,
– treated in vacuo 2 hours at 950°C.

The internal bursting pressure depends, other things being equal, on the bonding area between the corrugation and the skins. It is obvious that if the area increases the bursting pressure will also. However, the welding nuggets are not stresses, only in pure traction, but rather are subjected to combined forces and this mode of stress is not easily withstood by brittle bonds.

This test can therefore give information on the change in the assembly from two aspects:

– increase in bonding areas,
– degree of embrittlement of the assembly.

The following table recapitulates the bursting pressures of various test-pieces and shows the improvements made by post-welding heat treatment:

Test-pieces		*Untreated welds*	*Treated 2 hours under 10^{-5} torr*		
			850°C	*900°C*	*950°C*
Bursting pressure (bars)	1st series	80 85	141 119		180 200
	2nd series	48 50		140 142 144	

Another type of comparative test has also been made. It corresponds to a general stressing very close to the real conditions of use. It comprises repeated bending-shearing stressing of a beam under a central load.

Figure 23 presents the Wöhler fatigue strength curves for alternating bending-shearing stress, respectively for untreated titanium TA6V4 resistance welded specimens and those treated in vacuo for 2 hours at 900°C.

The value of this heat treatment is obvious; it increases by 50% to 90% the fatigue strength limits in the range 10^5 to 10^7 cycles. These improvements are largely attributable to the elimination by diffusion bonding of the notch effect at the ends of the resistance-welded nuggets.

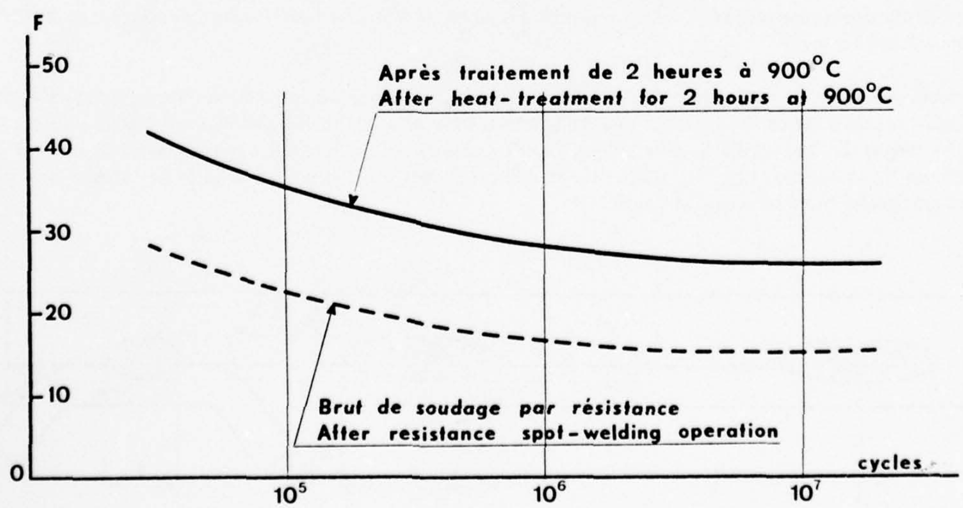
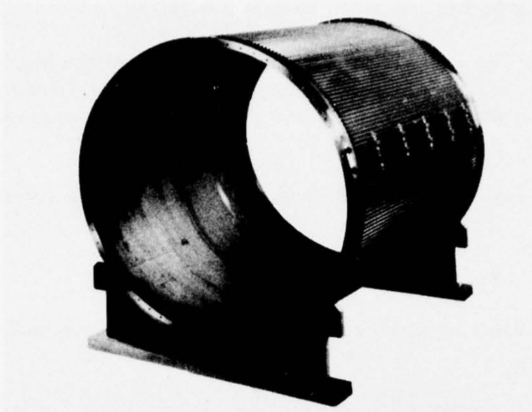


Figure 23

An application on engine scale, financed by the Direction des Recherches et Moyens d'Essais (France) has been made on a reheat duct SNECMA/M53, which underwent bench trials with success (Fig.24).



Canal de rechauffe de moteur SNECMA/M53
Post-combustion duct for SNECMA/M 53 engine
Figure 24

In conclusion, the technique consisting in the heat treatment of the NORSIAL titanium alloy sandwich material, firstly spot resistance welded with rolls, for example for 2 hours in vacuo at 900°C in the case of alloy TA6V4, offers very great indisputable advantages, as to the mechanical strength properties of the material, both in static and fatigue stress. These improvements are due to:

- metallurgical homogeneity between the base metal and the zones heat affected by the resistance welding,
- a relaxation of stresses arising from the welding,
- an increase in the bonding areas of the claddings and corrugated cores by solid state diffusion, under the "hammering" forces of welding only, and reducing the notch effects at interfaces.

This technique and its beneficial results have been described in this paper in the case of application to a particular sandwich material. It seems evident that it can be used for all sorts of welded structures.

METHOD OF QUALITY CONTROL OF WELDS BY INFRA-RED THERMOGRAPHY

The inspection of the assembling of sandwich materials is always a difficult problem, whether the materials are adhesive bonded, brazed, or welded. But in particular when the sandwich material is assembled by welding its non-destructive inspection is a problem, to which up to now there has been no entirely satisfactory solution. This lack is especially felt in the aerospace industry, which requires, for obvious reasons of safety, formal assurances as to the quality of the assemblies made.

The defects in resistance welded spots in general and also those in welded corrugated-core sandwich structures can be of various types. One of the most serious is the non-conformity of the dimensions of the weld nuggets to those expected. The length L, the width l, may be less than (or greater than) specified, the penetrations P_1 and P_2 may be different from those desired (Fig.25). When one of them is about zero the point is said to be "stuck" and the assembly has practically no mechanical strength.

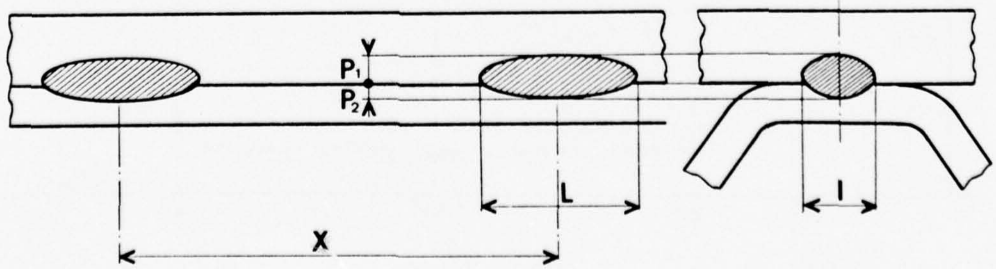


Figure 25

The welding pitch or interval between two consecutive weld points X has also to conform to the specifications.

Other internal defects at weld points can appear: cracks, shrinkage holes, porosity, "spitting" point (expulsion of molten metal) or burning.

All these defects can arise from extremely diverse causes, such as:

- welding machine faults, either in the timing of the free welding energy or ignition failures of the electronic switching, or again variations in the pressure of application of the welding rolls against the elements to be welded, or incorrect rate of advance of the rolls, etc.,
- physico-chemical condition of the surface of the elements to be assembled,
- non-uniformity of the elements to be assembled,
- the quality of the electrodes as regards their shape, hardness, geometry, etc., by electrodes is to be understood also the rolls, the tables or forms and the intermediate conducting elements and even the copper wire sometimes fitted to the welding rolls (Figures 5 to 10),
- the quality of electrical contacts, for example between the elements to be assembled or again between the elements and the intermediate conductors,
- shunting of current prematurely, etc.

The usual checks of resistance welds are predominantly destructive ones, for example micro- or macrographic examinations of sections, tests of mechanical strength in shear (traction or torsion), snatch strength tests or "unbuttoning". All these tests are made on representative samples of the assembly to be made, or by sampling some items in a large batch, therefore they cannot absolutely guarantee all the welds made.

Radiographic inspection by X-rays is not destructive, however it is often difficult to apply and not easy to interpret in the case of resistance welding. It enables most of the internal defects of weld spots to be revealed but the assessment of the dimensions of fused nuggets is generally not possible and that of penetration even less so. Moreover, this type of check is necessarily made *a posteriori* and often, for reasons of convenience or cost, long after the making of the welds. In this case malpractices can affect numerous assemblies before they can be detected.

There are other methods of inspection which can be applied *a posteriori*, which use magnetic or ultrasonic phenomena, etc. None is entirely certain or satisfactory.

The test procedure which we have tried and evaluated and which we are going to describe enables weld defects to be detected non-destructively and immediately after each welding operation, which, we note, proceeds at a high rate, and, notably, to assess exactly the volumes of welding nuggets.

In principle, the method consists of reconstituting, in the form of a temperature graded visible image, the infra-red radiations emitted by each weld spot during its cooling, at an exact instant after the electrical pulse making the weld.

For example, in the case of the welding of a sandwich structure with a stainless steel corrugated core, the melting temperature of the stainless steel, which is about 1450°C determines an infra-red emission whose maximum value places it, by Wien's formula, at a wavelength: $\lambda_{max} = B/T = 2898/(1450 + 273) = 1.7\,\mu m$ approx. (B: constant of the black body, T: temperature in °K of the emitting body). During cooling we are interested in the temperatures to 200°C, which correspond to an IR emission whose maximum level is at the wavelength $\lambda_{max} = 2898/(200 + 273) = 6\,\mu m$ approx.

These two limits have enabled us to select the IR radiation detector capable of covering the whole spectrum so as to achieve the examination with the maximum detection power. The most suitable detector in these wavelengths corresponds to an indium antimonide (InSb).

Figure 26 shows the way we have proceeded in the case of the welding described by Figures 7 and 10, in a view perpendicular to that of these figures. The welding roller is carried by a welding head, which moves in the direction shown by the arrow F . For clarity the wire and the welding transformer are not shown. The weld spots marked a, b, c, d, and e have already been made, f is in course of forming, the spot e is being examined. The reconstitution of the infra-red radiation from this weld spot in the form of a visible image is made by the cine-camera fixed on the welding head, which picks up the infra-red flux with a special lens and focusses it on to the detector (InSb), stabilised with liquid nitrogen. At this stage the IR radiation is tranformed into electrical signals which are sent to a display unit which provides the processing by modulating the electron beam from a cathode screen on which the image is formed.

This image is a "map" of the temperature levels, which, subject to prior calibration, can be graduated and each isothermal zone given an absolute temperature.

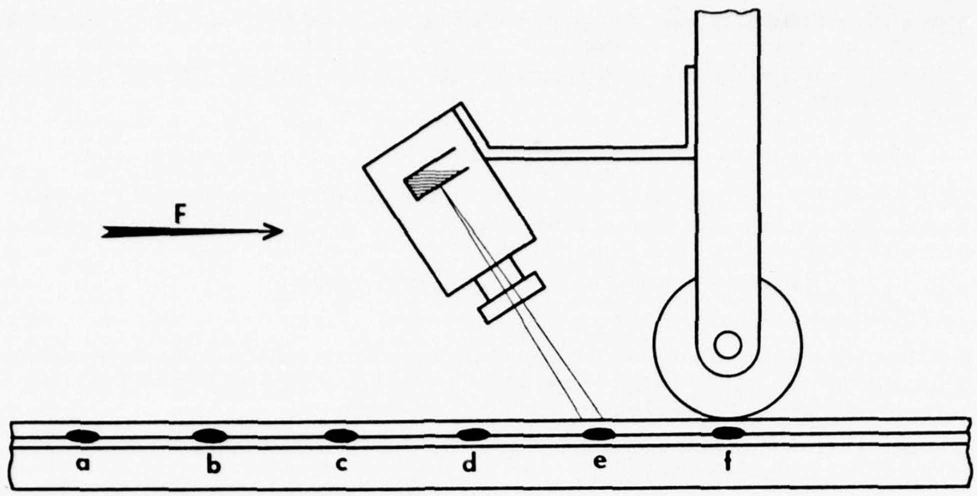


Figure 26

Figure 27b shows some results obtained with a type 750 IR camera and a cathode colour monitor, type CM 701-750, made by AGA AKTIELOBAG, in the welding and observation conditions described by Figure 26.

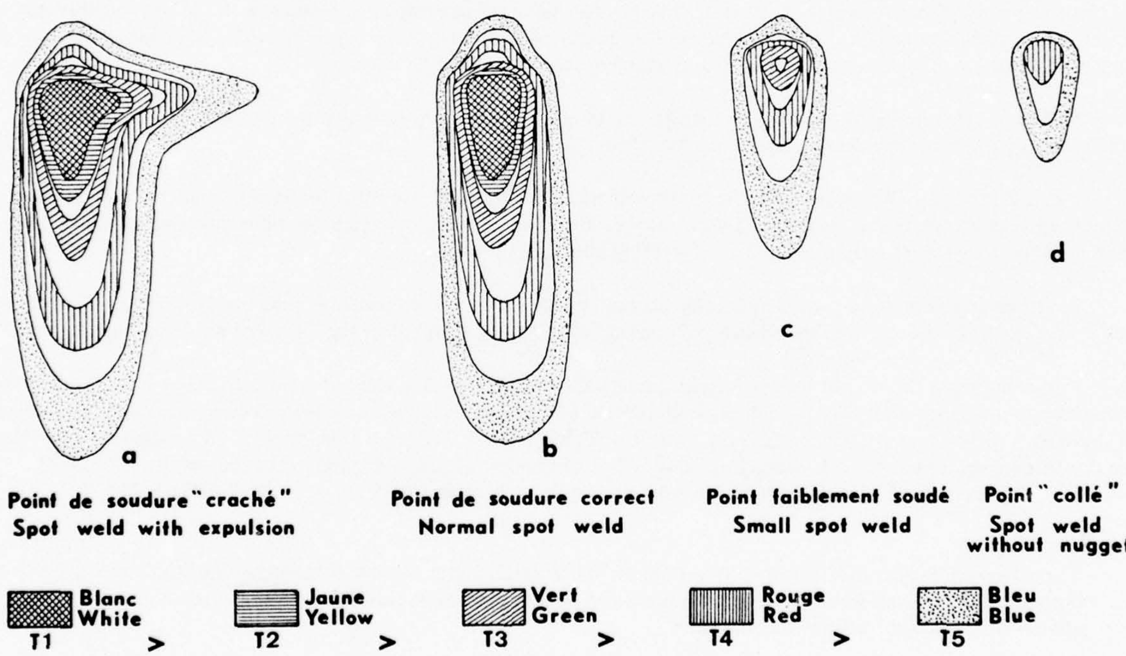


Figure 27

Figure 27b is the isothermal "map" obtained when the weld spots are correct, i.e. conform to the required specifications. The other isothermal maps are those of weld spots having characteristic faults. Figure 27c is that of a weak weld spot, that is, having dimensions L, l and P_1 and P_2, explained by Figure 25, which are below the required dimensions. The defect is perfectly detected by the elimination of the yellow isotherm zones corresponding to the temperature T_4 and white corresponding to T_5. Moreover, the other isothermal zones, blue (T_1), red (T_2) and green (T_3) have shapes and areas obviously changed compared with those of a correct weld. The isothermal map 27d is that of a "stuck" weld spot, that is the penetrations P_1 and P_2 are practically nil. In this case the isothermal zone green, corresponding to temperature T_3 has disappeared and the image has become very small. The isothermal map 27a is that of a "spluttered" weld point, that is the electrical energy during welding having been excessive – in view of the other welding parameters – the weld spot has become very large and molten metal has been expelled. In this case the changes of the isothermal zones, compared with those for a correct point, are obvious.

Figure 28 shows the comparison between the thermal image of a weld spot made with an electrical pulse of suitable duration, i.e. 0.02 sec (28a) and a spot made with a pulse reduced by half, i.e. 0.01 sec (28b).

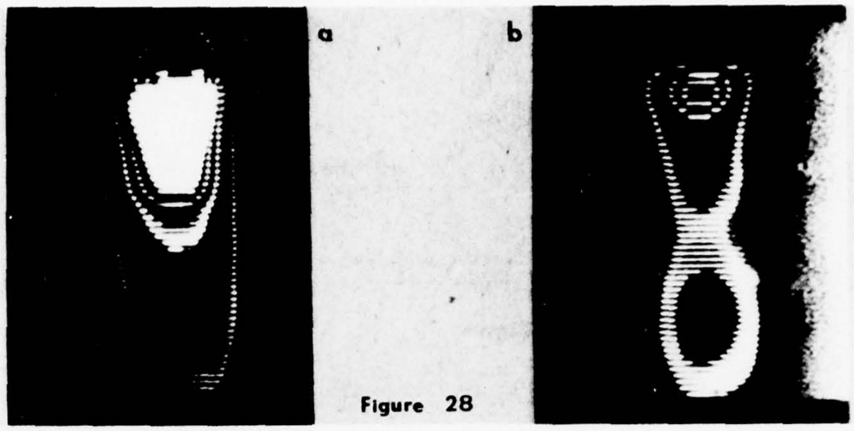


Figure 28

Figure 29 shows, as comparisons with the image of a correct spot weld, the images obtained when the electrical contact between the corrugated core and intermediate conductor is defective (29b) or when that between the core and the cladding is disturbed (29c).

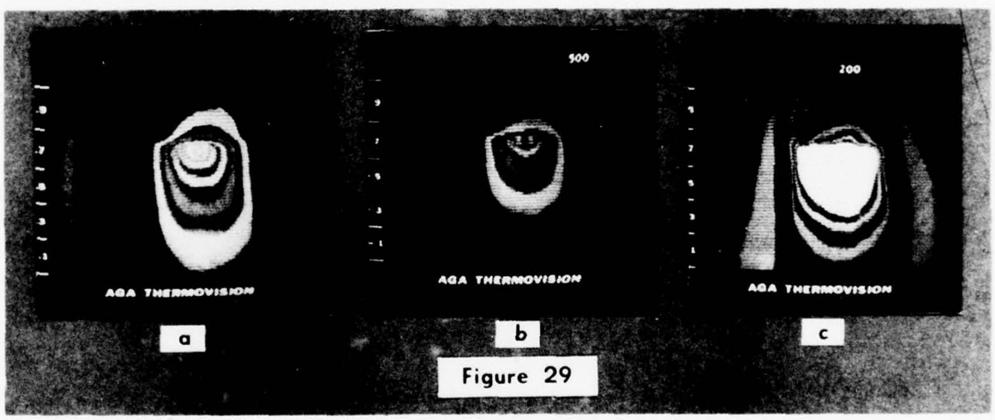


Figure 29

The check of the quality of the weld and of its conformity with that required by the specifications is made by comparison of the thermal "map" obtained for each weld spot with a standard reference map.

This comparison can be made visually by the operator of the welding machine, who is capable of assessing without any other aid the most important defects such as "sputtered" or "stuck" spots, on the CR screen.

For a closer analysis, observation can be facilitated by the addition between the screen and the observer's eye of the image of the standard reference map traced on a transparent support of plastic and coloured in the colours complementary to those which appear on the colour TV screen. Figure 30 shows this arrangement in the case of isothermal maps similar to that of Figure 27b. In the case where the isothermap map of the weld spot being checked conforms to the standard, the composition of the colours which appear on the cathode screen and which are seen by the observer, through the complementary coloured transparent screen, form for the observer a "map" of uniform brown colour, as can be seen on the example of Figure 31a.

On the other hand, in the case where the isothermal "map" of the spot being examined differs from that of the standard, the attention of the observer is aroused by zones strongly coloured yellow, green, red, blue, orange, violet, which come either from the cathode tube through the uncoloured zones of the intermediate screen and the coloured zones which are not of complementary colours, or from the intermediate screen illuminated by the white parts of the cathode tube. Figure 31b shows clearly this revealing phenomenon, for a defective weld, where the contour lines for the isothermal zones are shown broken for the reference map and continuous for the map of the point being inspected.

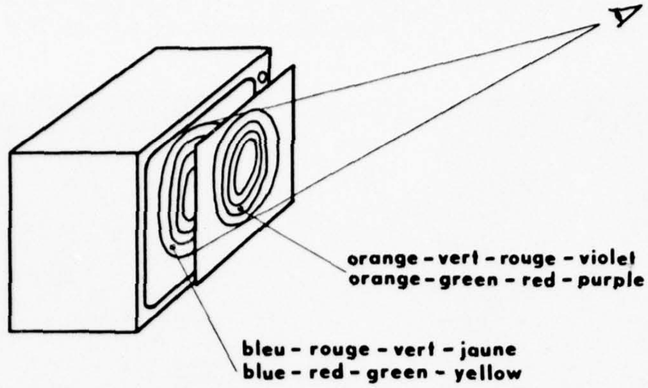


Figure 30

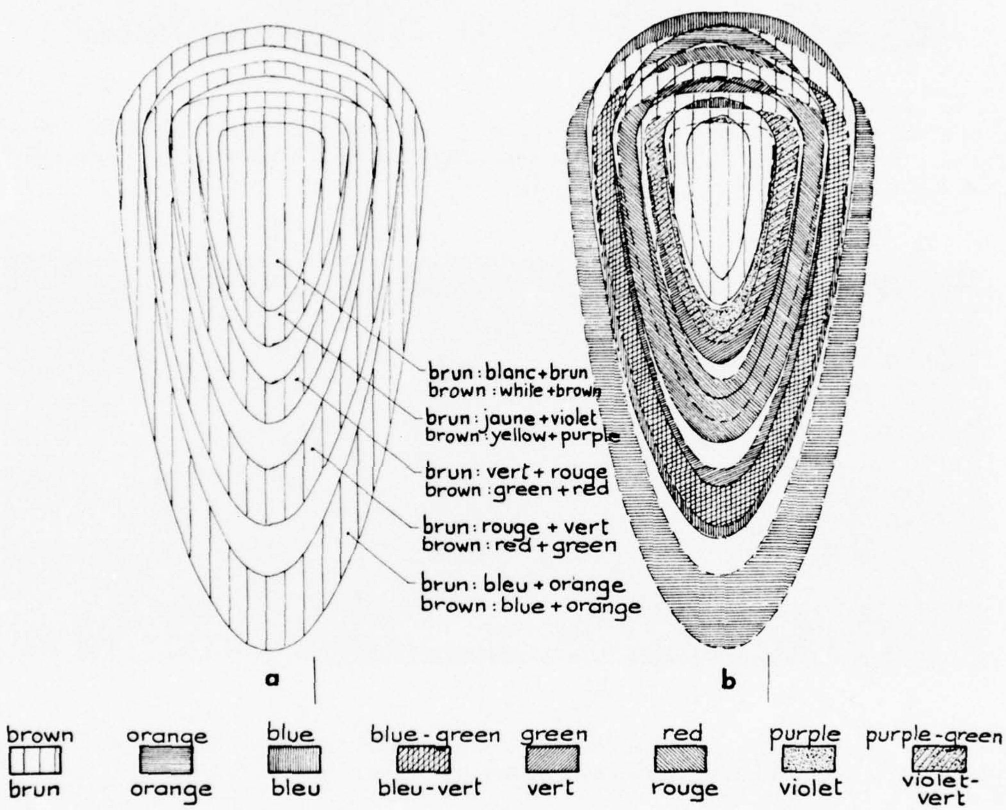


Figure 31

The comparison of the thermal "map" of a weld point with that of the standard of a reputedly correct weld, which constitutes the quality control procedure, can also be made automatically by electronic equipment. As an example, Figure 33 outlines the working of an electronic equipment which enables the automatic analysis of a number of geometric parameters of one or two or more defined isothermal zones of each weld spot made.

Figure 32 explains, as an example, the geometric parameters which are monitored for an isothermal zone by equipment of the type described by Figure 33. These parameters are: the length L_0 , the width L_A , the area S , the symmetry $E_2 - E_1$.

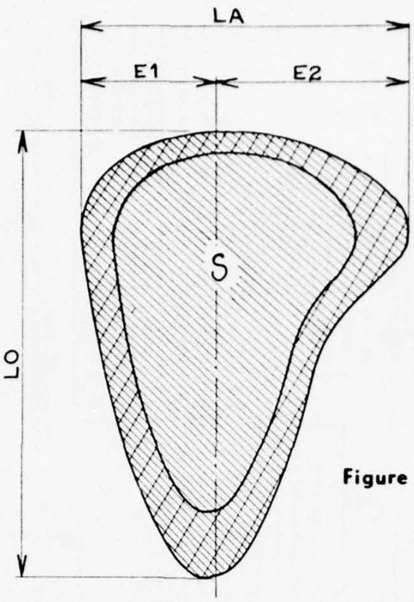


Figure 32

The working diagram of Figure 33 describes the equipment for processing the video signal which enables automatic monitoring of the above parameters. In the case of any anomaly in one of the parameters, whose upper and lower tolerances are previously set on an electronic control and monitoring bay, the equipment arranges for the welding machine to stop.

In conclusion, although all the possibilities of quality control of resistance welds by an infra-red thermographic method have not yet been fully explored, the results we have obtained, some of which have been presented here, demonstrate the future prospects for this method. It seems particularly well suited to repetitive welding at a high rate, which is the case for assembling corrugated core sandwich material, because it can be fully automated and, moreover, is non-destructive and applied during fabrication provides immediate auto-checking.

CONCLUSIONS

The metal sandwich material with welded corrugated core called NORSIAL, developed by Aérospatiale S.N. (France) is the object of continuing research aimed at its improvement and extension of its field of application. During some of this work two techniques have been tried and evaluated: a heat treatment procedure applied after resistance welding has, in some cases, enabled the mechanical strength characteristics to be appreciably improved, especially in fatigue; an infra-red thermographic control method, sensitive, reliable, convenient, capable of being automated, non-destructive, used during fabrication and of quite reasonable cost, enables the quality of the resistance welding to be guaranteed.

Although these two techniques have been described in this paper within the special context of a sandwich material, for which we have carried out our evaluations, we think that they can also be applied, with some modifications, to any other welded structures.

Figure 33 overleaf

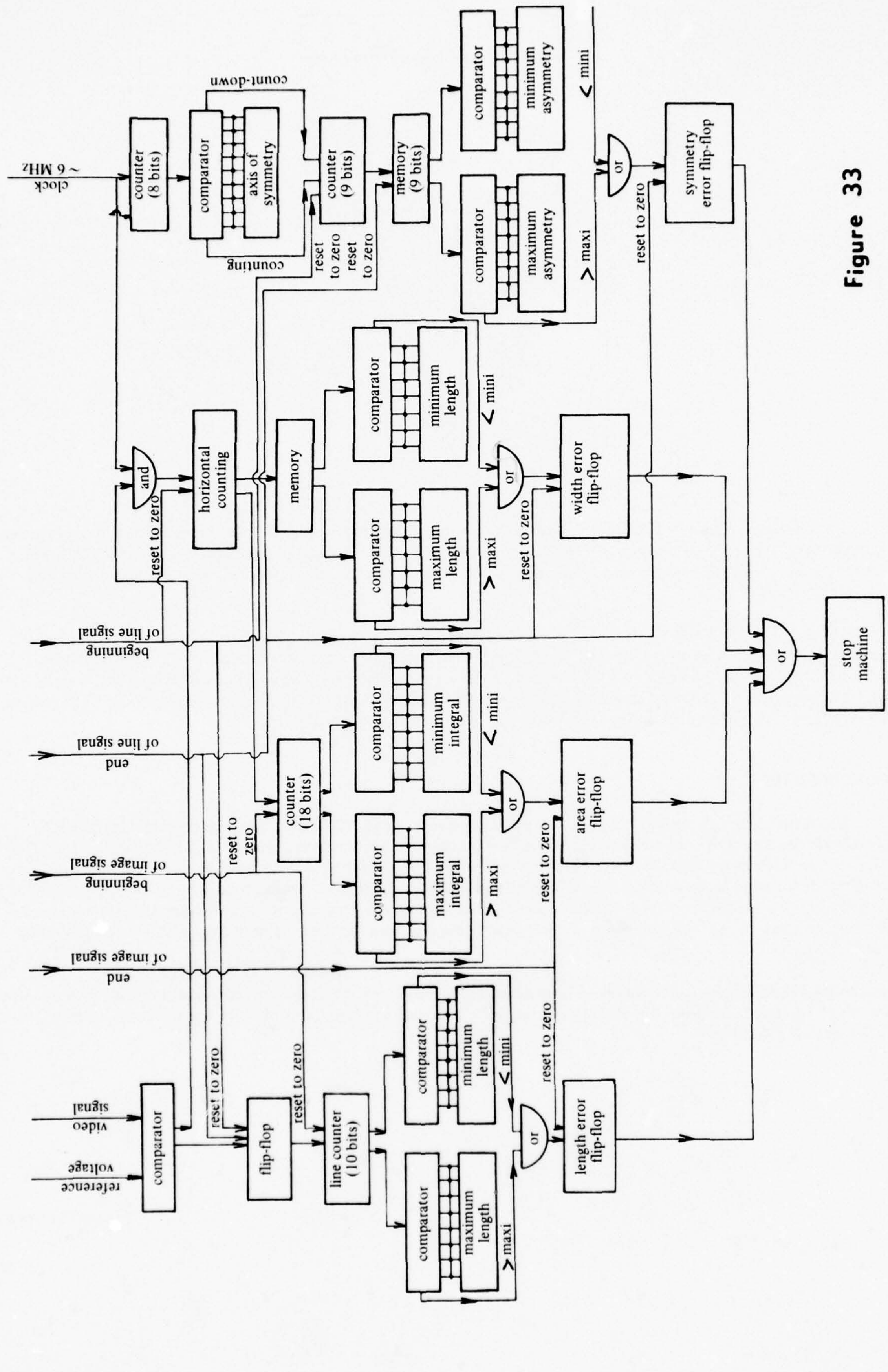


Figure 33

Figure 33

Advanced Manufacturing Techn.ques in Joining
of Aerospace Materials

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